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**EFFECT OF LOCALIZED ACOUSTIC EXCITATION ON
THE STABILITY OF A LAMINAR BOUNDARY LAYER**

FRANCIS J. JACKSON
MANFRED A. HECKL

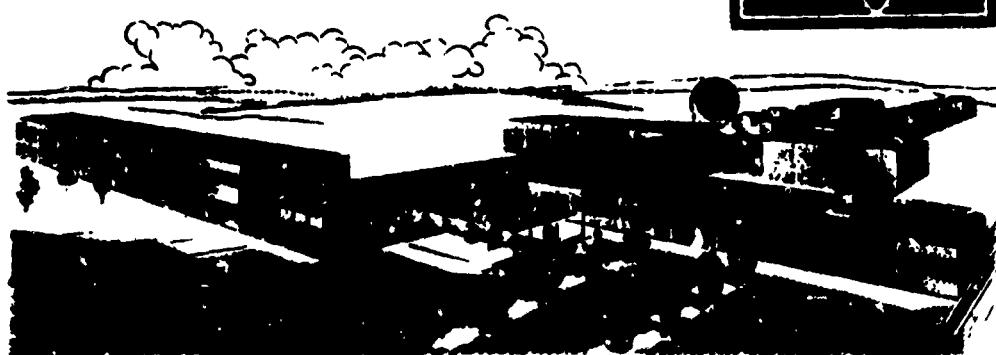
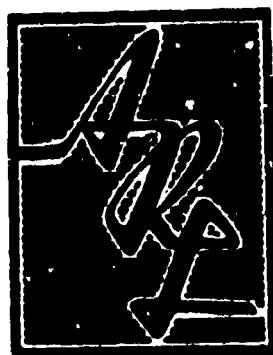
BOLT BERANEK AND NEWMAN INC.
CAMBRIDGE, MASSACHUSETTS

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**EFFECT OF LOCALIZED ACOUSTIC EXCITATION ON
THE STABILITY OF A LAMINAR BOUNDARY LAYER**

**FRANCIS J. JACKSON
MANFRED A. HECKL**

**BOLT BERANEK AND NEWMAN INC.
CAMBRIDGE, MASSACHUSETTS**

JUNE 1962

**Contract AF 33(616)-8001
Project 7084
Task 70138**

**AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

FOREWORD

This final technical report was prepared by Bolt Beranek and Newman, Inc., Cambridge, Massachusetts, on Contract AF 33 (616)-8001 for the Aeronautical Research Laboratories, Office of Aerospace Research. The work reported herein was accomplished on Task 70138, "Investigation of the Interaction of Sound and Shear Flow" of Project 7064, "Research on Aerodynamic Flow Field" under the technical cognizance of Dr. Max Scherberg, Thermo-Mechanics Research Laboratory, ARL.

The authors acknowledge the assistance in various phases of the work of their colleagues at Bolt Beranek and Newman Inc., Professor Ascher H. Shapiro and Dr. Richard M. Fand* of Massachusetts Institute of Technology, Professor Joseph Kestin of Brown University, and The F. W. Dixon Company of Cambridge, Massachusetts. The many valuable suggestions and comments of Dr. Scherberg are also gratefully acknowledged.

*Now at Bolt Beranek and Newman, Inc.

ABSTRACT

As part of a program to uncover the influence of induced surface vibrations on the stability of a shear flow boundary layer, investigations have been performed utilizing a localized surface source of acoustic energy to generate disturbances in a laminar boundary layer flow. Explorations have been carried out over a frequency range of from 50 to 10,000 cps, using input sound pressure levels of up to 145 db re 0.0002 dynes/cm². Results are presented which indicate the effect of sonic parameters (frequency, amplitude) on both the mean and fluctuating components of the boundary layer flow. Induced boundary layer oscillations are discussed, where appropriate, in terms of the stability theory of Tollmien and Schlichting. Studies of distortion of boundary layer oscillations are described and the role of such distortion in producing transition is discussed. Nonlinear secondary flows (streaming) generated by the localized source are also treated. Exploration of the influence of sonic excitation on premature transition produced both by increasing the free stream turbulence level and by use of a tripping wire are described.

Results indicate that localized excitation affects the stability of the laminar boundary layer in accordance with results first obtained by Schubauer and his co-workers employing a different experimental system. In the case of the tripping wire, results indicate that excitation of a certain frequency and amplitude can interact with the periodic vortex shedding in such a way as to forestall premature transition. In no case have localized sonically induced flows (streaming) been found to influence the incipient processes which govern transition.

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SECTION I

INTRODUCTION

The transition of a shear flow boundary layer from laminar to turbulent flow forms one of the major problem areas of the aeronautical sciences. Associated with this transition are such phenomena of practical importance as marked changes in the drag and heat transfer rate when the flow becomes turbulent. Attempts to obtain a detailed understanding of the mechanisms by which transition occurs have been the subject of many outstanding investigations over the years (Refs. 1-7). While these investigations have greatly contributed to an understanding of the mechanisms of transition, much is yet to be learned about the detailed physical aspects of the problem and possible means for its control.

The present report describes initial results of an investigation which is being carried out by Bolt Beranek and Newman Inc., under cognizance of the Aeronautical Research Laboratory, to ascertain the influence of sonic excitation on the shear flow boundary layer which exists adjacent to a surface exposed to a parallel steady flow.

The primary objective of our work is to increase our fundamental understanding of the mechanisms by which oscillations initiated at the surface of the test body and introduced into the boundary layer, influence the stability of the flow. Such knowledge should form a basic link to the overall problem of analyzing the influence of sonic excitation on the drag and heat transfer characteristics of fluid flow past an object.

The concept of utilizing sonic or ultrasonic oscillations to control the stability of a boundary layer is not a new one. Indeed, the original motivation for the studies reported on here was provided by a German patent which proposed that drag experienced by an airfoil could be effectively reduced by providing sonic excitation of the surface "skin" of the airfoil. Although the exact processes by which such drag reduction might be accomplished are not discussed in the patent, the concept presented does give rise to the question as to whether or not localized sonic excitation of a boundary layer can have any beneficial effect on its stability. In particular, one might ask if transition of a boundary layer from the laminar to the turbulent regime can in any way be forestalled by inducing oscillations, other than those normally present, into the boundary layer.

It is well known that the shape of the velocity profile in boundary layer flow affects the stability of the boundary layer in a fundamental way. This profile can be influenced by several external factors. In the work described here, we have investigated the influence

on the shape of velocity profile produced by localized vibration of the surface adjacent to the flow.

Adequate investigation of such phenomena would, of course, require several years of research effort. In the present study, however, we have confined our attention to one specific problem, namely: ascertaining the influence of a highly localized oscillatory surface excitation on an adjacent boundary layer flow.

The localized source is of interest since it generates a boundary layer disturbance which is initially confined to a small region of the surface, and thus does not simultaneously induce disruption of the normal flow situation at all points on the surface. Furthermore, such a source is known to generate highly localized time independent secondary flows. The latter appear in the form of small circulations which are confined to a thin layer of the fluid medium adjacent to the source. For situations to be encountered here, this layer is usually much thinner than the normal shear flow boundary layer. The speed of these circulations varies as the square of the acoustic (oscillatory) particle velocity, and thus they may be important at moderately high acoustic intensities.

A question thus arises as to whether or not such sonically induced steady flow (commonly termed acoustic streaming) can significantly influence the local shear flow velocity profile and thereby influence the stability characteristics of the boundary layer.

Accordingly, in our present work, we have aimed at answering the following questions, namely: 1) Can localized oscillatory surface excitation of shear flow boundary layer have any influence on its stability characteristics, other than to initiate an unstable Tollmien-Schlichting wave; 2) Can secondary sonically induced steady flows (i.e., acoustic streaming) be of sufficient magnitude so as to modify the normal boundary layer velocity distributions and thereby influence stability?

Results indicate that the answer to both of the questions framed above is negative. In no case studied has it been possible to observe any influence of localized surface excitation on the incipient processes which govern natural transition of a boundary layer flow other than those expected on the basis of conventional stability theory.

Furthermore, for the situations studied, here sonically induced steady flows within the boundary layer (acoustic streaming) are found to have no measurable influence on its stability. Information obtained in the course of this study does, however, provide some detailed insight as to the role of local sonically induced boundary surface oscillations on the stability of the laminar boundary layer.

We have essentially divided our work into three phases:

- 1) Studies of the influence of sound on both steady and oscillatory laminar boundary layer velocity profiles well upstream of the point of natural transition,
- 2) Studies of the effects produced by sonic excitation on transition introduced by a tripping wire upstream of the localized acoustic source, and
- 3) Studies of the effects of sonic excitation produced near the point of natural transition.

The results of these studies are presented in the following sequence: Section II contains a detailed description of the experimental system employed in our investigations. Evaluation studies performed to ascertain the characteristics of the wind tunnel and sonic excitation system are discussed in Section III. Section IV presents results of a detailed study of the influence of sonic excitation on the laminar boundary layer, viewed in the light of conventional linear stability theory. In Section V, the interaction between the sonic disturbances and turbulence induced both by means of a tripping wire and by increases in the free stream turbulence is described. Section VI contains a discussion of the roles of secondary acoustic phenomena in influencing the shear flow boundary layer. A summary of these studies and conclusions based thereon are presented in Section VII. Section VIII discusses areas where further studies would be useful.

SECTION II

EXPERIMENTAL SYSTEM AND ITS CHARACTERISTICS

The experimental program necessitated the design, construction, and evaluation of two major equipment items, namely, a low turbulence wind tunnel and a test body which incorporates a localized source of acoustic energy at its surface. Evaluations of these items were carried out by use of a hot wire anemometer system. Each of these items is described subsequently in detail.

A. WIND TUNNEL

The wind tunnel was designed in collaboration with Professor Ascher Shapiro, of the Department of Mechanical Engineering at the Massachusetts Institute of Technology. The tunnel is an induction type of square cross section, and has an overall length of 30 ft. The test section is approximately 16 inches square by 6 feet in length. A cross-sectional view of the tunnel is shown in Figure 1. To achieve low turbulence levels in the test section, a suitably contoured transition section of contraction ratio 16 is used to couple to a 64 inch square inlet section. The latter contains a 15 inch deep honeycomb composed of 1/2 inch hexagonal cells in front of three #16 mesh screens, mounted in tandem, followed by three #30 mesh screens to reduce the turbulence of the flow before it enters the transition section. The separation between screens is approximately 5 inches.

Since low ambient noise levels in the test section are a prerequisite for successful experiments involving sonic excitation, a muffler has been provided between the downstream end of the test body and the centrifugal blower which provides the flow. This muffler is of the deep treatment type described by Cremer (Ref. 8), and is effective at frequencies as low as about 20 cps. The duct through the muffler section has been tapered so that it also acts as a diffuser for the flow. An eight foot glass fiber wedge is placed in the duct through the muffler section to absorb high frequencies. This arrangement provides a significant reduction of blower-generated noise in the test section.

The room in which the tunnel inlet is located acts as a settling chamber. False ceilings have been removed from this room and that containing the blower. The plenum above thus acts as the return flow loop of the tunnel.

The blower is a Westinghouse type 3024 driven by a 2 hp motor which provides a maximum flow of 6000 cfm. This places an upper limit of approximately 70 ft/sec on flow speeds in the test section. This limit can be increased if necessary by use of a faster drive arrangement on the blower, or by decreasing the cross-sectional area of the test section. Flow speed is varied both by means of a variable speed

drive and a choke arrangement on the exhaust of the blower. The blower is mounted on spring type isolation mounts to reduce structure-borne vibration and is connected to the muffler section by means of a flexible coupling as shown in Figure 1.

The tunnel is constructed mainly of plywood and was fabricated by the F. W. Dixon Co., Cambridge, Massachusetts. Salient flow characteristics of the tunnel are described in a later section of this report.

B. THE TEST BODY

The test body employed in conjunction with the wind tunnel is shown in Figure 2. Since the shear flow boundary layer associated with a flat plate geometry has been a subject of intensive investigation, both from an experimental and theoretical point of view, and is reasonably well understood, we had originally planned to employ a flat plate mounted near the center line of the tunnel. Subsequent study indicated, however, that the advantages of a flat plate could be retained if a properly designed test body of cylindrical cross section were used, and that the cylindrical geometry presented two additional advantages. These are:

- 1) In any duct of non-circular cross section secondary flows occur transverse to the axis of the main stream flow (Ref. 9). While these flow speeds are typically quite small compared to the mean flow through the duct, they can be of the same order of magnitude as typical acoustic perturbation speeds. Thus, if acoustic phenomena are to be considered as possible perturbation mechanisms in the shear flow boundary layer, duct-generated secondary flows should obviously be avoided or at least minimized. The ideal way to accomplish this would be to employ a cylindrical test body in a cylindrical tunnel. However, from the standpoints of time, economy, and ease of fabrication, the geometry of a square tunnel with a cylindrical test object has been chosen as a best compromise.

Aerodynamically, flow past a cylindrical test body is analogous to the situation of two-dimensional flow over a semi-infinite flat plate, as long as typical boundary layer displacement thicknesses are small compared to the curvature of the cylindrical test body. For the test body employed here, this condition is fulfilled except in the vicinity of the forepoint of the ellipsoidal nose piece. As will be seen in the next section, effects produced by this contoured nose piece necessitate defining an equivalent leading edge in order that the flat plate analogy be a valid one. However, once the position of this equivalent leading edge is obtained, the analogy between our geometry and the flat plate is found to hold quite well.

- 2) The use of a cylindrical test body allows placement of the sound generator within the test object itself. This eliminates external protuberances on the body which might interfere with the flow over the object. If such interference occurred, it would probably be necessary to provide a rather elaborate, and no doubt costly, means to allow the flow to bypass the externally instrumented test body downstream of the observation area.

The method used to generate localized oscillations at the surface of the test body is also shown in Figure 2. The sound source is a small loudspeaker mounted coaxially within the cylindrical body. The sound is injected into the external medium by means of the circumferential opening on the body. The width of this opening can be varied by moving the forward section of the test body along the shaft as shown in the figure.

In this way, one has, in effect, a small vibrating piston - consisting of the mass of moving air in the slit - which excites the boundary layer adjacent to the test body. The advantages of this system are fourfold:

- 1) It is easy to construct, as it has no moving parts.
- 2) The inertia of the piston is just the plug of air in the slot. This plug of air can be excited into motion much more readily than a solid piston, thus reducing the source power requirements.
- 3) Quite a bit of information has been gathered on the acoustic streaming flow associated with such a source.
- 4) Mechanical piston systems are always such that they are operated only at specific frequencies and amplitudes corresponding to the resonant frequencies of the system. The air-piston can be operated over a much wider range of frequencies, and is thus more useful as an exploratory tool.

The forepart of the test section consists of an appropriately contoured nose section to permit smooth buildup of the laminar boundary layer. The cylinder is mounted on a thin metal plate, which rests on the floor of the tunnel test section, by means of three struts. These struts have a cross section corresponding to that of a NACA 65-009 Laminar Flow Airfoil in order to minimize interference with the flow in the test section. The entire assembly can be moved along the axis of the test section.

There are, of course, also some disadvantages associated with such an arrangement. As noted above, it is necessary to determine

the "equivalent leading edge" of such a test body in order to treat the flow as being similar to that of two dimensional flow over a flat plate. In addition, if this analogy is to hold, studies must be confined to situations where the boundary layer displacement thickness is small compared to the curvature of the test cylinder. Finally, with the sonic system employed here, efficient excitation can be provided only up to a frequency of about 10 kc.

However, results indicate that these restrictions have not imposed serious limitations on the scope of our experimental studies.

One further point should be noted, namely, the question as to the effect of the circumferential slit itself on the stability of the laminar boundary in the absence of sonic excitation. Measurements indicate that, for sufficiently small slit widths, the slit of itself does not give rise to boundary layer instability.

C. INSTRUMENTATION FOR MEAN VELOCITY AND TURBULENCE MEASUREMENTS

A block diagram of the anemometer system employed in measuring both mean and fluctuating velocity components is shown in Figure 3. The basic component of the system is a model HWB Flow Corporation Hot Wire Anemometer unit. This unit consists of a D.C. bridge network for measurement of steady velocity components; fluctuating velocity components are measured by feeding the output of the bridge circuit into an amplifier which incorporates a frequency compensation network. Such compensation is necessary to nullify the increased lag in response of the hot wire to fluctuating signals as their frequency increases. For the system employed here, compensation is needed for fluctuations above 100 cps. The compensation network is adjusted by means of a square wave calibrator incorporated in the HWB unit. When correctly compensated, the output of the amplifier closely reproduces the fluctuations measured by the hot wire probe.

The compensation network has the detrimental characteristic that as the frequency of the input signal increases, the electrical noise output of the amplifier also increases. It is therefore customary to employ a low-pass filter between the amplifier output and the metering apparatus as shown in Figure 3. Measurements have indicated that most of the energy due to fluctuating velocity components is confined to the frequency region below 5000 cps. For this reason, a 5000 cps low-pass filter was employed to eliminate undesired high frequency noise.

The output of the amplifier can be fed either directly into an oscilloscope and random signal voltmeter connected in parallel, or, if a spectral analysis of the fluctuating velocity component is desired, through a 1/3 octave band filter. The random signal voltmeter employed here is a true rms voltmeter having a variable integration time. One can thus obtain a short or long term root mean square value of the magnitude of the fluctuating velocity components.

The hot wire probe is calibrated for steady flow velocity measurements by measuring the pressure drop between the inlet section, just past the screens, and the exit from the test section. The mean flow velocity is then calculated on the basis of the pressure drop and correlated with the D.C. current necessary to balance the anemometer bridge. For determining the magnitude of small fluctuating velocity components in the direction of the mean flow, a probe can be calibrated in terms of the rms magnitude of the fluctuating component u' and mean flow velocity by means of the equation

$$u' = \frac{C U_0}{I^2 - I_0^2} \sqrt{\frac{e_f^2 - e_0^2}{e_s^2 - e_f^2}} \quad (1)$$

In the above equation, C is a constant which depends upon the circuit parameters of the anemometer bridge, I and I_0 represent, respectively, the current needed to balance the bridge for a mean flow U_0 , and a zero flow condition. The term e_f^2 and e_s^2 represent, respectively, the rms voltage output of the amplifier developed by the fluctuating component u' and that produced by the square wave (calibration) generator. The voltage e_0 represents the output noise level of the hot wire system.

Eq (1) is used only when the magnitude of the fluctuating velocity component is less than 20% of the mean flow velocity. Above this level linearization assumptions introduced in deriving Eq (1) are invalid, and a more exact analysis is required. Furthermore, since the oscillatory velocity is essentially normal to the mean boundary layer flow at positions directly above the center of the slit, Eq (1) cannot be employed to determine the acoustic particle velocity at such points. Values of u' computed at such points by use of Eq (1) would probably be a measure of the periodic changes in the mean flow velocity caused by the boundary layer "riding" the superimposed oscillation.

A more direct technique for measuring the rms excitation velocity is discussed in the next section.

SECTION III

EXPLORATORY STUDIES - WIND TUNNEL AND SONIC EXCITATION SYSTEM

Prior to the start of the experimental investigations a series of evaluation tests were performed to ascertain the aerodynamic properties and limitations of the wind tunnel both with and without the test body installed, and to determine the basic characteristics of the acoustic field generated by the localized source. These studies are described below.

A. FLOW CHARACTERISTICS OF THE TUNNEL

The hot wire instrumentation is installed in the tunnel in such a way as to permit two-dimensional scanning of the flow field; horizontal scanning can be accomplished in a vertical plane through the center line of the tunnel test section over a range of about 30 cm; vertical scanning can be accomplished over the entire distance between the top and bottom walls of the test section. Vertical positions of the probe can be determined to within 0.01 mm.

A typical distribution of the mean, or D.C., velocity across the test section (with the test body removed) at a point approximately 45 cm from the entrance is shown in Figure 4. The co-ordinate Z has its origin at the top of the test section. One observes that the flow speed is uniform over the major portion of the test section and decreases towards zero as the walls are approached. It will be noted that the flow is not symmetrical about the center line of the test section, but that the velocity begins to decrease towards the top wall at first rather slowly and then rather rapidly in the region between the top wall and a point about 8 cm below. The reasons for the lack of symmetry are at present unknown.

This lack of symmetry should not seriously influence the boundary layer flow in the vicinity of the test body, since this region of non-idealized tunnel flow is at least 6 cm (approximately 15 times the boundary layer thickness assuming typical experimental conditions) away from the surface of the test body.

Furthermore, the effect of this region of asymmetry was investigated experimentally. Various combinations of steady and sonically induced (oscillatory) components of the flow velocity were measured at distances ranging from near zero to several boundary layer thicknesses above the test body. In no cases were variations in flow profiles observed at distances greater than 1 to 2 cm from the surface of the test body.

Typical turbulence levels associated with the D.C. velocity distribution presented in Figure 4 are shown in Figure 5. We define

turbulence level, expressed in percent, as $100 \frac{u'}{U}$, where u' is the rms value of the fluctuating velocity component along the longitudinal axis of the test section, and U is the corresponding value of the D.C. flow velocity.

As shown in Figure 5, the turbulence levels are greatest near the walls of the test section. Over the major portion of the test section the level is relatively uniform, having a value of about 0.4% for the indicated flow speed of 50 ft/sec. Note that there is an asymmetry in the turbulence level distribution near the top of the tunnel wall, corresponding to the asymmetry in the D.C. flow field discussed earlier. Again, measurements indicate that this is not a source of interference with phenomena occurring near the boundary layer along the test body.

A third octave band analysis of the turbulent fluctuations near the center of the test section is shown in Figure 6.* It will be noted that most of the free-stream turbulent energy is contained within the frequency range 100 to 3200 cps. A pronounced peak in the spectrum is seen to occur at a frequency of 1250 cps. The source of this peak is uncertain. It is believed to be a residual effect produced in the test section by the vortex shedding which occurs behind the screens upstream of the contraction section. However, on the basis of the usual Strouhal number relationship between frequency of vortex shedding f , mean flow speed U , and characteristic dimension of the obstacle interacting with the flow,

$$f \approx 0.18 \frac{U}{d}; \quad (2)$$

the expected shedding frequency of the #30 mesh screens is approximately 720 cps (based on the wire diameter of the screen). This is not in good agreement with the observed peak frequency of 1250 cps; however, it should be remembered that we have neglected interaction effects between adjacent wires which make up the screen. There is thus some question as to what characteristic dimension d should be employed in Eq (2).

The turbulence levels shown in Figure 5 represent maximum turbulence levels inherent in the operation of the tunnel. At lower flow speeds, the turbulence level decreases considerably, e.g., at a flow speed of 25 ft/sec, the turbulence level is only about 0.2%.

* The third octave band levels can be converted easily into spectral density. See e.g., L. L. Beranek "Acoustic Measurements," (John Wiley and Sons Inc., 1949).

B. MEAN BOUNDARY LAYER PROFILE ABOVE THE TEST BODY

Tests were performed with the cylindrical test body installed in the tunnel without sonic excitation. Of major interest was the determination, at various flow speeds, of the laminar boundary layer profile which exists at different points along the test body. In particular, it was desired to compare the various measured boundary layer velocity distributions with the characteristic flat-plate zero-incidence boundary layer velocity profile developed analytically by Blasius (Ref. 10). Figure 7 presents results of measurements of the D.C. velocity distribution for two different mean flow speeds U_∞ and four different points x along the test body. The origin for the measurement of x will be discussed subsequently. The distance z , measured upwards from the surface of the test body, and the corresponding velocity $u(z)$ are expressed in non-dimensional form, respectively, in terms of a boundary

layer thickness $\sqrt{\frac{v x}{U_\infty}}$ (where v is the kinematic viscosity of air), and the mean flow speed U_∞ for purposes of comparison with the Blasius velocity profile, also shown in the figure.

As can be seen from Figure 7, good agreement exists between our measurements and the velocity distribution predicted on the basis of the Blasius solution for flow over a flat plate. The agreement between theory and experiment does, however, require some discussion, particularly because we assume, for reasons discussed earlier, that the flow past the cylindrical test body can be treated, insofar as boundary layer phenomena are concerned, as being equivalent to zero incidence flow over a flat plate.

The analogy between our experimental system and the flat plate situation should not, of course, be expected to hold at the forepart of the test body, where the leading edge consists of an ellipsoidal surface incorporated into the design of the test body along which buildup of the laminar boundary layer can occur. This raises the problem of defining a point near the forepart of the test body which will in a sense be an "equivalent leading edge" when the flat plate analogy is employed. This point lies somewhere between the forepoint of the streamlined nose piece and the point where it joins the cylindrical test body. Location of this point has been determined empirically by measuring boundary layer profiles at various points along the boundary, computing the boundary layer thickness δ in terms of various distances x along the test body, and then comparing profiles obtained with the Blasius profile. Results of a series of such measurements indicate that good agreement between measured data and the Blasius profile is obtained when the origin of x is taken to be a point 6 inches downstream of the forepoint of the contoured nose piece (the nose piece has a total length of 12")

Results indicate that this technique permits determination of the equivalent leading edge to within about ± 1 inch. No measurable changes have been found in the location of this point at different flow speeds. It should also be noted that these results are qualitatively in accord with analytical results obtained by Schlichting (Ref. 9) in treating zero incident flow over elliptical cylinders. Subsequent measurements, to be discussed in Section IV also bear out this result, in that the analogy between the flat plate situation and our arrangement holds quite well if the equivalent leading edge is taken to be this latter point. Accordingly, in all results discussed in this report, Reynolds numbers, boundary layer thicknesses, etc., are based on distances along the test body measured from this equivalent leading edge.

C. CHARACTERISTICS OF THE SONIC EXCITATION SYSTEM

1. The Driving System

The geometrical configuration of the sound source has already been discussed in the preceding section. We describe here the manner by which sonic excitation is provided, and the calibration techniques employed to obtain a correlation between measured excitation levels and acoustic particle velocities generated in the boundary layer.

The driving unit consists of a 4" permanent magnet loudspeaker which can be moved longitudinally within the test body as shown in Figure 2. Connections to the speaker are brought out from the rear of the test body and through the wall of the muffler section. A Hewlett Packard Model 200CD audio oscillator provides pure tone signals in the frequency range 0 to 10,000 cps which are fed into the loudspeaker through a power amplifier. Sound pressure levels within the test body are monitored by means of a calibrated microphone mounted coaxially within the test body immediately behind the plane of the circumferential slit. The test body is designed so that the circumferential slit in the test body is at a plane of maximum acoustic pressure associated with any one of a number of possible resonance modes within the tube. For the frequency range found to be of importance in our studies, the only resonance modes produced within the tube are longitudinal ones; cross (radial) resonances are unimportant. At moderate frequencies, sound pressure levels of up to 145 db (re: 0.0002 dynes/cm²) have been produced at the slit opening. For experiments discussed in the present report, the slit width seldom exceeds 3 mm.

Since the vibrating air in the slit acts like a piston in a hard wall, the most important parameter that affects the boundary layer is the velocity and frequency of the piston, i.e., the velocity of the air in the slit. In the following section we describe how the velocity can be measured and how it is related to the sound pressure inside the test body. Subsequently, we give measurements on the velocity distribution in the vicinity of the slit. It will be seen that this

distribution is very similar to what one would expect for a small piston in a hard wall.

2. Calibration Techniques

An absolute calibration of the hot wire anemometer for acoustical particle velocities poses a difficult problem, since the sensitivity of the hot wire depends in a complicated way on the mean flow speed and on the direction of the acoustical particle velocity with respect to the mean flow.

Fortunately, in our experiments this difficulty could be circumvented, since we deal, for the most part, with sound pressure level below 130 db. In this range of intensities, we can assume that a linear relationship exists between the sound pressure and the acoustic particle velocity. This means that the acoustic particle velocity can be calculated from a knowledge of the sound pressure levels measured by the microphone within the test body, if we first obtain a general calibration curve.

Such a calibration curve is shown in Figure 8. Here the frequency dependence of the acoustic velocity at the slit for a sound pressure level of 113 db inside the test body is presented. (The position at which the velocities were measured is indicated in the sketch in Figure 8.)

It can be seen that the velocity decreases inversely with frequency. This is what one expects from a consideration of the acoustic impedance of such a slit.* The calibration curve in Figure 8 was obtained in two steps:

- 1) To determine the sensitivity of the hot wire at one particular amplitude and frequency, it was placed in the velocity maximum of a very intense 1500 cps standing sound wave in still air.** The acoustic velocity of this position is of known amplitude and produced a certain reading of the hot wire anemometer. With this measurement accomplished, the hot wire was placed in the wind tunnel and located at the slit (see sketch in Figure 8). Then for the same frequency (1500 cps) the

* The "effective mass" calculated from Figure 8 is somewhat larger than the mass of the air in the slit. This is probably due to the so called "end correction" discussed in texts on acoustics.

** These measurements were made at M.I.T. with equipment used to measure the effect of sound waves on heat transfer. The assistance of Dr. Richard M. Fand is gratefully acknowledged.

sound pressure in the test body was increased until it reached the hot wire reading that was obtained originally. In this way, the ratio between the magnitudes of the internal sound pressure and the acoustic particle velocity at the surface of the test body was obtained. The measurement in the tunnel was made without mean flow.

- 2) To determine the frequency response curve shown in Figure 8, the sound pressure within the test body was maintained at a constant level. The hot wire output was then measured. This procedure was repeated for various frequencies in the range between 50 and 2000 cps. In order to maintain a linear relationship between the A.C. velocity and the hot wire output voltage, the measurements were made in the presence of a mean flow of 46 ft/sec.* In this way, relative velocities for various frequencies were determined. By employing the previously described calibration at 1500 cps, the curve shown in Figure 8 was obtained.

3. The Acoustic Velocity Distributions Near the Source

The localized nature of the acoustic field produced at the surface of the test body can be seen from the curves shown in Figure 9. Here the local acoustic particle velocity relative to that measured at the center of the slit is plotted as a function of the co-ordinates x' and z . The former measures horizontal distance along the test body, while the latter measures distance upwards from the surface of the test body; the origin of these co-ordinates is the center of the slit (i.e., the sound source). One observes, in Figure 9, that the acoustic particle velocity decreases quite rapidly as the distance from the slit increases; in the case of the vertical velocity distribution (Figure 9a), the acoustic velocity 1 mm from the slit is less than the acoustic velocity at the slit by a factor of approximately 13. In the case of the horizontal velocity distribution, the velocity 10 mm away from the source (at a vertical distance of 0.5 mm) is a factor of 10 less than the velocity at the source. These curves indicate that the slit behaves approximately as a line source of acoustic energy, in that the velocity amplitude decays inversely with the distance from the center of the slit. Thus the major portion of the acoustic velocity field is effectively confined to a region within a few mm of the source. For purposes of comparison, typical conditions ($U_\infty = 45$ ft/sec) the boundary layer thickness at the slit is approximately 2.8 mm.

* Use of hot wire techniques in measuring oscillatory flow characteristics requires the presence of D.C. bias flow in the tunnel. That portion of the hot wire signal arising solely from the oscillatory disturbance is obtained by the use of appropriate narrow band filters in series with the hot wire signal detector.

SECTION IV

THE EFFECT OF LOCALIZED SONIC EXCITATION ON THE LAMINAR BOUNDARY LAYER

A. GROSS INTERACTION EFFECTS

Preliminary investigations utilizing the localized sound source were carried out to obtain information on gross effects of the sonic excitation in influencing the turbulence level near the test body.

Initial measurements were performed with the hot wire placed about 1.5 cm downstream of the source and about halfway into the laminar boundary layer (5~3 mm). The results are shown in Figure 10, where spectral distributions of typical relative turbulence levels, namely, the ambient level in the presence of sonic excitation compared to that which arises solely from inherent fluctuations in the mean flow (i.e., the free stream turbulence level) are plotted.* Due to the large range of the various levels involved, it is convenient to express the relative levels on a logarithmic (db) scale).

As one might expect, at sufficiently small excitation amplitudes, one observes only a linear superposition of the sonically induced disturbance and the ambient or background turbulence level. This linear superposition is observed at sonic excitation amplitudes up to and including a sound pressure level of 125 db (measured inside the test body as described in the previous section).

As the sound pressure level is increased, one still observes superposition of the fundamental excitation frequency as well as an increase in the magnitude of the second harmonic. At a sound pressure level of approximately 138 db, a sudden transition occurs, i.e., the nature of the spectrum changes completely and the overall turbulence level is increased considerably, as shown by the 140 and 145 db curves in Figure 10. Hence the laminar boundary layer flow is "tripped" into turbulent flow only above a certain level of sonic excitation. This effect has been found to be frequency dependent. This latter point is discussed in more detail in the next section.

The results simply illustrate that there is a limited range of sonic amplitude (and, as discussed later, frequencies) in which studies

* The actual bandwidth of the excitation frequency peaks is much narrower than would be inferred from Figure 10. This is because the excitation frequency (450 cps) lies midway between two third octave bands.

of sound and laminar shear flow interactions should be performed. At sonic amplitudes below the ambient (background) turbulence fluctuation amplitudes, little effect can be expected to be produced by the acoustic signal. On the other hand, if sonic amplitudes become sufficiently large, the entire boundary layer is triggered into rapid transition from laminar to turbulent flow, thus obscuring any orderly interaction processes which may be occurring.

B. EFFECT OF EXCITATION FREQUENCY ON BOUNDARY LAYER STABILITY

As noted in the previous section, the sound pressure level needed to trip the boundary layer into turbulent flow at the local source depends strongly upon the excitation frequency. Accordingly, the relationship between frequency, sonic amplitude, and the stability of the boundary layer was investigated. In order to prevent sonically induced transition from occurring at the sound source, relatively low level sonic excitation was employed (for actual levels employed see Figure 11), and measurements were taken some distance downstream from the source. It is found that low sonic amplitudes at certain frequencies produce premature transition at points downstream of the localized source. The various frequencies which are conducive to premature transition were determined in the following manner: In a typical experiment, the hot wire was placed approximately 40 cm downstream of the acoustic source and approximately 2 mm above the test body. The loudspeaker was driven at various frequencies and amplitudes, and the resultant internal sound pressure was measured by means of the monitoring microphone described in the preceding section. By employing techniques discussed earlier (see Figure 8) the acoustic particle velocity at the source was determined. The output of the anemometer was monitored by means of the oscilloscope, and the sound pressure level at a given frequency was adjusted to the minimum value necessary to cause transition. Since a relatively small change in excitation amplitude can initiate transition, a precise measurement of this minimum level can be obtained at each frequency.

Figure 11 shows results of two such series of measurements. The curves shown represent plots of acoustic particle velocity at the source necessary to produce transition at the specified downstream point, as a function of frequency. Since these curves show pronounced minima we can conclude that for each mean flow velocity (and for each position along the surface of the test body), there is a frequency at which a very small amount of acoustic energy is sufficient to trip turbulence. This frequency, which will be referred to as the "critical" frequency, depends, of course, on the flow speed and the location of the hot wire.

The preceding measurements were extended to frequencies higher than those shown in Figure 11 but no additional "critical" frequencies could be found. For frequencies above 2000 cps the acoustic energy

radiated from the loudspeaker was not sufficient to cause transition. Measurements were attempted at frequencies as high as 10,000 cps.

C. TOLLMIEN-SCHLICHTING THEORY OF STABILITY

In their now classic investigations, Schubauer and Skramstad (Ref. 6) found that random fluctuations present in a boundary layer flow undergo a frequency selective amplification within the boundary layer as they propagate downstream. This gives rise to almost sinusoidal boundary layer fluctuations at some distance downstream of the leading edge. It was also found that these sinusoidal fluctuations could be correlated very well with the Tollmien-Schlichting stability curve (see Figure 13 of Ref. 6).

The existence of the minimum excitation velocities associated with the critical frequencies discussed in connection with Figure 11 indicates that selective amplification of the sonically induced boundary oscillation is occurring as it propagates downstream. In order to explain this result in more detail, it will at this point prove useful to summarize the salient conclusions of the Tollmien-Schlichting theory of stability.

The flow velocity is assumed to be composed of an average time independent component U , upon which is superimposed a fluctuating component u' ; an essential restriction upon the validity of the theory is the condition that $\frac{u'}{U} \ll 1$. The superposition of the small component u' upon the mean flow velocity in one direction presents to the stationary observer the appearance of wave motion.

If the stream were uniform, the fluctuations would take on the attributes of a traveling wave having a propagation velocity equal to that of the stream. In a boundary layer, the velocity of wave propagation can be shown to be less than the maximum velocity of the flow. Assuming the fluctuating components to be of the form $u' \sim e^{i(\beta t - \alpha x)}$, the theory proceeds, by developing the appropriate differential equations of continuity and conservation of momentum in terms of a straight forward perturbation approach, to describe the relationship between the parameters as U , u' , α , and β . The situation treated is that of two-dimensional flow, and the theory confines itself to studying only the behavior of small disturbances; three-dimensional and finite amplitude disturbances are not within the province of the theory. Studies (Ref. 12) have shown, however, that two-dimensional theory leads to the prediction of critical Reynolds numbers somewhat lower than those derived assuming a three-dimensional disturbance.

The major result of the Tollmien-Schlichting theory is the prediction of the frequency (or wavelength) of neutral disturbances for

flows at various Reynolds numbers. This result is usually presented in terms of a stability diagram such as that shown in Figure 12. This curve represents essentially the boundary between the regimes of stable and unstable boundary layer fluctuations. From the diagram one may predict whether or not, for a given Reynolds number (e.g., location downstream of the leading edge) a disturbance of a given frequency will either amplify (unstable), decay (stable) or remain unchanged (neutral).

D. COMPARISON OF EXPERIMENTALLY DETERMINED CRITICAL FREQUENCIES WITH TOLLMIEN-SCHLICHTING STABILITY CRITERIA

The critical frequencies observed in the course of our investigations and discussed in part B of this section, have been compared with the theoretical curve of neutral stability in Figure 12. In this figure $\beta/2\pi$ is the critical frequency, x the distance from the equivalent leading edge to the position at which the transition is observed, and v is the coefficient of kinematic viscosity. The data lie close to the upper branch of the theoretical stability curve. This behavior is in accord with similar behavior found and explained by Schubauer (Ref. 6).

Although no special care was taken to establish precise control over pressure gradients along the test body, as was done by Schubauer, our measured points are seen to form a relatively good fit to the neutral stability curve predicted on the basis of the Tollmien-Schlichting stability theory.

In explaining this result, it must be kept in mind that the point at which transition is measured is relatively far downstream from the localized excitation source (i.e., the slit). Accordingly, a disturbance that is generated at the source passes through a wide range of Reynolds numbers and possibly through regions where it may amplify or decay, as it propagates downstream to the position occupied by the hot wire probe. Since these regions of amplification and decay occupy different positions for different frequencies, one might expect a disturbance of a certain frequency to undergo a maximum amount of amplification as it propagates downstream. One would expect two dimensional oscillations to develop to a maximum amplitude by such amplification at a point close to the second branch of the neutral stability curve (Figure 12).

This conclusion has already been stated, as well as confirmed experimentally, by Schubauer and Skramstad (Ref. 6), and is in agreement with similar conclusions set forth by Lin (Ref. 13).

In the present investigation, the total amplification of the sonically generated disturbance is not measured directly; instead, the occurrence of transition is used as an indicator of those disturbances which have undergone a high degree of amplification in propagating

downstream. We thus assume that turbulence is generated whenever the boundary layer fluctuations exceed a certain limit. This limit can be achieved in either of two situations; namely, 1) that whereby a disturbance which undergoes a small amount of amplification as it propagates is generated with a sufficiently large excitation amplitude, and 2) that whereby a small excitation amplitude generates a disturbance which undergoes a sufficiently high degree of amplification. It is the latter situation which pertains to the present problem, insofar as we conclude that the frequency at which the minimum excitation velocity (Figure 11) produces transition is identical with the frequency of a disturbance which has undergone maximum amplification. This frequency, in turn, lies very close to the second branch of the neutral stability curve of the Tollmien-Schlichting theory (Figure 12).

E. DISTRIBUTION OF SONICALLY-PRODUCED FLUCTUATIONS IN THE BOUNDARY LAYER

In order to determine whether or not there are additional similarities between boundary layer fluctuations studied by Schubauer and Skramstad, who used a vibrating ribbon to generate boundary layer disturbances, and those obtained here using the localized surface source, the velocity profiles of sonically induced laminar boundary layer fluctuations were measured and compared both with Schlichting's theory and results obtained by Schubauer and Skramstad. Measurements were made by exciting the flow and monitoring the hot wire output voltage at different points above the test body. The results are shown in Figures 13 to 16. In order to compare results obtained in different experiments the distance z between the hot wire and the surface of the test body

has been normalized by the boundary layer thickness $\delta = 5\sqrt{\frac{V_x}{U_\infty}}$. In all cases the boundary layer thickness is based upon the distance x from the equivalent leading edge defined earlier. The excitation frequency f , the mean flow speed U_∞ , and the distance x are given in each figure. Location of the point corresponding to the parameters discussed here are shown on the stability diagram of Figure 12; here the point associated with results presented in Figure 13 are identified by the symbol 13, etc.

One observes that for the two excitation frequencies (180 cps and 320 cps) which fall within the unstable region of the Tollmien-Schlichting stability diagram (see Figure 12), the magnitude of the hot wire output signal is larger for the position further downstream from the sound source; i.e., the signal is amplified as it propagates downstream. Conversely, for the two frequencies (90, 780 cps) which fall within the stable region of the stability diagram, the sonically induced disturbance decays as it propagates downstream.

Another interesting feature of these results is that, except for the case $f = 780$ cps, the boundary layer velocity fluctuations pass

through a minimum value at a certain value of $z/6$. These minima are indicative of phase reversal points predicted for neutral disturbances by Schlichting (Ref. 5). In our experiments, this phase reversal was not directly observed, since the hot wire output signal is rectified. Therefore, the point of minimum amplitude must serve as an indication of the point at which phase reversal occurs. At this point, the signal should be zero. However, minimum levels which could be resolved were limited by the background noise level, which was of the order of 5 mv.

The values of $z/6$ at which phase reversal occurs agree reasonably well with theoretical results. Schlichting predicted (Ref. 5) and Schubauer (Ref. 6) measured a value of $z/6 \approx 0.7$ for neutral disturbances. For non-neutral disturbances, Zaat (Ref. 14) has calculated a value of $z/6 \approx 0.45$ for the phase reversal point. Our results lie within this range.

Additional measurements were performed to determine details of the amplification and deamplification of the sonically generated boundary layer oscillations. Results obtained are similar to those reported by Schubauer and Skramstad (Ref. 6) (cf. Figure 37 of their report) which were obtained in their very low turbulence wind tunnel. The agreement of our results with the studies performed by Schubauer et al, indicate the adequacy of our experimental system for sensitive stability measurements, and provide some insight as to the sensitivity of the boundary layer flow to the various sonic parameters.

F. AMPLIFICATION AND DISTORTION OF BOUNDARY LAYER FLUCTUATIONS

Figures 17 through 21 show photographs of the hot wire output signal displayed on an oscilloscope for positions downstream of the source. Figure 17 shows the effect of increasing the sound amplitude. Sound pressure levels (SPL) measured inside the test body in the vicinity of the slit are given at the left of each curve.* Since the output of the hot wire varies with distance from the test body, as shown in Figures 17 to 21, attempts were always made to place the hot wire at the point of maximum signal output, i.e., very close to the test body.

As can be seen, the signal approximates a pure tone oscillation at low amplitudes. With an increase in amplitude, the signal becomes

* In order to maintain a pattern suitable for photographing, it was necessary to change the attenuator settings on the oscilloscope between photographs; the numbers to the right of the photographs in Figure 17 indicate the amount by which the oscilloscope signal was decreased relative to the initial signal level (top photograph) in each set. This has been necessary only in connection with results shown in Figure 17.

distorted and finally degenerates into the random fluctuations which are characteristic of turbulence. Of particular interest are the appearance of characteristic sharp large amplitude "spikes" (see Figure 17, 117 cps) which appear just prior to transition to completely turbulent flow. These spikes have been observed and discussed by other investigators, but the reason for their appearance is not known. An understanding of the mechanism by which these spikes are produced would contribute significantly to a more precise understanding of the transition process.

The distortion of the excitation signal is due mainly to the generation of higher harmonics in the boundary layer. This can be seen more clearly by the photographs shown in Figure 18. The top photograph is similar to those shown in Figure 17; however, the lower three photographs of Figure 18 illustrate the relative amplitudes of the fundamental tone, the first harmonic, and the second harmonic of each of the signals shown in the upper photograph. As can be seen, the harmonic content of the boundary layer disturbance increases markedly with increase in amplitude. It should be pointed out that this distortion of the fundamental signal occurs in the boundary layer, and is not produced by distortion of the excitation signal within the test body.

Figure 19 shows the effect of increasing the distance between the sound source and the hot wire, while keeping the sound pressure level constant.

One result that is evident upon inspection of Figure 19 is that a low frequency excitation signal (by low frequency we mean that for a given Reynolds number the corresponding Tollmien-Schlichting frequency of the disturbance should lie within the region of stable disturbances on the characteristic stability diagram) distorts as it propagates downstream. This effect is more clearly illustrated by the photographs shown in Figure 20. Here, the upper photograph shows a disturbance generated at constant sound pressure level, at three successive points downstream. The two lower photographs illustrate the result of a harmonic analysis of two of these disturbances. As can be seen, the harmonic content of the disturbances increases markedly with distance downstream. These observations provide a partial explanation of the transition mechanism in the low-frequency range. It appears as if the small vortices generated periodically in the viscous sublayer at the source break up at some distance downstream, thereby giving rise to disturbances of higher frequencies which lie within the domain of unstable Tollmien-Schlichting disturbances and are thus amplified as they propagate downstream. These latter disturbances are what may consequently give rise to transition.

In order to check that this concept, which is also in agreement with theoretical considerations by Lin (Ref. 13) is a correct one, the

photographs shown in Figure 21 were made. These photographs show the results of experiments in which the flow was disturbed by a 100 cps excitation signal.* The hot wire output at different points x downstream was filtered through a 1/3 octave band pass filter. Although the attenuator settings on the oscilloscope were not changed for signals shown within a given photograph, it was necessary to make such changes between photographs, i.e., when changing the frequency analysis band, in order to permit reasonably good reproduction of the observed waveform. Hence, information as to amplification rates, etc., should not be inferred directly from a comparison of different photographs. One can see in Figure 21, however, that the portion of the signal centered about 100 cps decreases somewhat as the hot wire probe is moved downstream. However, that part of the signal which is centered about 200 cps increases by almost a factor of two. It is interesting to note that although these higher harmonics were generated, i.e., that some type of nonlinearity was present, each of the harmonics, qualitatively followed the predictions of Tollmien-Schlichting theory. Those harmonics in the stable regime decayed as they moved downstream, while those in the unstable regime were amplified. This is in accord with Lin (Ref. 7) who has stated that the nonlinear effects first appear in the generation of harmonic modes in the critical layer before the distortion of the mean flow is noticeable.

It has been verified experimentally that the higher harmonics that appear in Figure 21 are due to a nonlinear effect (e.g., breaking up of vortices) in the boundary layer and not to distortion produced by the loudspeaker or the slightly nonlinear impedance of the slit. This has been done as follows: The anemometer probe was placed at the slit, and the amplitude of the first harmonic (200 cps) was measured.

The oscillator was then adjusted to produce a fundamental signal of the same amplitude at 200 cps. Boundary layer disturbances produced by this 200 cps fundamental were then observed. It was found that the resultant fluctuations downstream of the slit were at least an order of magnitude less in amplitude than those observed when a 100 cps fundamental was employed. These results indicate that amplification of the small distortion produced by the sonic excitation system is not the cause of the 200 cps signal shown in Figure 21.

We do not as yet completely understand the changes that occur in a sonically induced high frequency boundary layer disturbance as it propagates downstream. It appears as though the sound signal were amplified sporadically, giving rise to "patches" of fluctuations, having fairly high amplitudes, followed by regions of fairly calm flow, as can be seen in Figure 19, (the photograph obtained using 450 cps

* The corresponding point on the stability diagram is shown in Figure 12.

excitation). This phenomenon seems to be similar in some respects to that found by Schubauer and Klebanoff (Ref. 11) using a spark to generate a boundary layer disturbance and to the water table experiments of Emmons (Ref. 15).

G. EFFECT OF SONIC EXCITATION ON THE MEAN BOUNDARY LAYER VELOCITY PROFILE

A series of measurements were made in an effort to determine whether or not sonic excitation in any way influences the mean (D.C.) flow velocity distribution in the boundary layer.

Experiments were performed using excitation frequencies from 50 to 10,000 cps. In most cases, the level of the exciting signal was increased up to the point where the signal triggered transition from laminar to turbulent flow. Results of these measurements indicate that, in the laminar regime, sonic excitation has no observable effect on the mean flow profile. This can be seen in Figure 22, where typical boundary layer profiles, obtained in the presence of a sonically generated boundary layer disturbance, are shown for both the laminar and turbulent flow regime. As can be seen in the figure, data obtained for the case of laminar flow form a relatively good fit to the characteristic laminar (Blasius) profile discussed in Section II. The velocity distribution obtained in case of the turbulent flow (triggered by increasing the sonic excitation level to 130 db) is shown by the dotted curve of Figure 22. This profile is characteristic of those associated with turbulent boundary layers.

SECTION V

EFFECT OF SONIC EXCITATION ON INDUCED TRANSITION

A. TRANSITION PHENOMENA PRODUCED BY INCREASING THE FREE STREAM TURBULENCE LEVELS

In order to determine whether or not sonic excitation near the point of transition can affect the boundary layer profile, the free stream turbulence level was increased from 0.4% to 1.3% at a mean flow speed of approximately 50 feet per second. This was accomplished by placing a grid composed of wires approximately 1.5 mm in diameter, spaced 3 mm apart, across the inlet of the wind tunnel test section. Transition then occurs at a critical Reynolds number of approximately 4×10^5 (based on the distance from the equivalent leading edge), which is approximately one order of magnitude lower than the critical Reynolds number to be expected with the grid absent. The point of normal transition is thereby moved correspondingly closer to the localized source.

Results indicate that sound signals of different levels and frequencies never move the transition point downstream. In fact when the sound signal is of sufficiently large amplitude, the point of transition is moved upstream.

In Figure 23 the oscillatory velocity (measured at the slit) necessary to cause turbulence is plotted as a function of frequency. As can be seen, the curve obtained here does not have as pronounced a dip as was characteristic of similar curves obtained in the absence of the grid (see Figure 11), indicating that critical frequencies such as discussed in the previous section are not observed at this higher free stream turbulence level. The slight dip in the curve of Figure 23 occurring at about 400 cps cannot be correlated with a Tollmien-Schlichting frequency. It appears that this minimum level is in some manner related to the vortex shedding frequency of the grid which, based on the characteristic Strouhal number, is approximately 400 cps.

B. TRANSITION INDUCED BY MEANS OF A TRIPPING WIRE

A grill, such as used in experiments described in the preceding section, produces more or less random fluctuations of the air flow. Another question is, however, how sound affects the somewhat regular disturbances (periodic shedding of vortices) that are introduced by a tripping wire mounted on the surface of the test body ahead of the localized sound source.

Figure 24 shows the results typical of some experiments performed using a tripping wire. The wire, approximately 1.6 mm in diameter, was placed 30 mm upstream from the slit. A small gap (approximately

1/10 mm) existed between the upper half of the test body and the wire. On the lower half of the test body, the wire was tightly fastened. Initially, the hot wire was placed a small distance behind the wire to determine the vortex shedding frequency. (The measured shedding frequencies of 790 and 1500 cps are shown as arrows in Figure 24. These values agree reasonably well with the expected frequencies predicted on the basis of the characteristic Strouhal number: i.e., 850 cps for $U_\infty = 28$ ft/sec, and 1650 cps for $U_\infty = 55$ ft/sec.) The hot wire was then moved 50 mm behind the localized sound source, i.e. to a point $x = 14"$. The curves in Figure 24 show the sound velocities measured at the source necessary to cause turbulence at $x = 14"$

These curves show two interesting features: 1) The sonic excitation frequency which most easily generates turbulence is close to the vortex shedding frequency. 2) In one case (at 500 cps) the curve is double valued. The second feature can be explained as follows: as the sound signal increased, the fluctuations became somewhat larger and suddenly at a certain level the flow became turbulent; for higher sound signals the flow returned to the laminar state (the fluctuations were even less than those without any sonic excitation) and finally at a certain higher sound level the flow became turbulent again.

This result would tend to indicate that for certain frequencies and certain amplitudes the disturbances generated by the tripping wire are canceled out by the sound. This seems to be possible if one postulates that the sound also influences the vortex shedding from the wire so that the right phase shift exists between the latter and the applied sonic signal.

SECTION VI

NONLINEAR SONIC PHENOMENA

As noted in the introduction to this report, we have aimed not only at ascertaining effects produced in the boundary layer by a localized oscillatory disturbance, but also effects which might be associated with localized secondary acoustic phenomena, e.g., the generation of steady circulatory flows (acoustic streaming) in the vicinity of the localized acoustic source. Acoustic streaming phenomena of the type one might expect to occur for our situation have been described by Ingard and Labate (Ref. 16).

Attempts were made to study such flows as might exist near the circumferential slit in the test body by means of smoke visualization techniques by introducing smoke through the slit. Some small scale circulatory streaming motion was observed to occur near the edges of the slit. These observations were made only in the absence of a mean flow in the tunnel using moderately large (in the vicinity of 125-130 db) excitation amplitudes, because superposition of a mean flow immediately obscured details of any circulatory phenomena occurring in the boundary layer. It appears that the mean flow obliterates the observed circulation for all conditions studied. This is borne out by use of the hot wire anemometer; the characteristics of the mean flow in the boundary layer are unchanged even though circulatory effects are observed without flow.

All results reported previously in this report are ascribable for the most part to the oscillatory nature of the localized sonic excitation when viewed in the light of the Tollmien-Schlichting stability theory. On the basis of these results it thus appears that secondary sonic phenomena such as acoustic streaming, when generated in a laminar boundary layer, have no observable effect on the incipient development of boundary layer instability.

We do not, of course, conclude that nonlinear effects, taken in the general sense, are unimportant in the transition process itself. As has been pointed out by Lin (Refs. 7, 13) and others, the Tollmien-Schlichting theory must be extended to include effects of finite amplitude disturbances in order to further understanding of the transition process, since unstable boundary layer oscillations amplify as they propagate downstream, thereby eventually invalidating the assumption of small disturbances invoked in the development of linearized stability theory. Recently, Benney (Ref. 17) has presented an extended theory of stability which takes into account the nonlinear effects generated further along in the transition region by the Tollmien-Schlichting boundary layer disturbances.

SECTION VII

SUMMARY AND CONCLUSIONS

Results described in the preceding sections indicate that the essential effect produced here by localized sonic excitation of a laminar boundary layer is to induce premature transition from laminar to turbulent flow. In general, the results indicate that the local source, when driven at moderately low excitation levels, produces small scale fluctuations in the boundary layer in much the same manner as the vibrating ribbon employed by Schubauer and Skramstad (Ref. 6) in their earlier studies of the transition process. As a consequence of its design, the localized source utilized here does, however, have a wider dynamic range over which linear fluctuations can be produced than a vibrating ribbon.

Of particular interest are the results obtained here which indicate that small scale boundary layer oscillations which lie within the low frequency region of stable disturbances (see Figure 12) can in many instances give rise to instability by the mechanism of harmonic generation as discussed in Section III. This conclusion is based on the observation that a low frequency signal undergoes distortion as it propagates downstream, and as a consequence generates higher order harmonics which usually lie within the unstable region of the characteristic stability diagram. These harmonics, which are generated in the boundary layer can thus be looked upon as secondary sources of incipient unstable fluctuations. The bursts of instability observed to occur when using sonic excitation (cf., e.g., Figure 19) which lies in the high frequency region of the stability diagram* cannot, however, be interpreted by means of a similar hypotheses. A precise explanation of this phenomena is yet to be found.

Results of experiments performed using a tripping wire to induce turbulence yielded the interesting result that such turbulence could, in certain cases, be forestalled by localized sonic excitation. It is most probable that this result comes about as a result of a phase cancellation between the periodic vortex street shed by the tripping wire and the periodic disturbance produced in the boundary layer by the sonic excitation. This hypotheses is strengthened by the observations made employing a grill to produce a higher free stream turbulence level, which moves the point of transition nearer to the localized source. Here, the rather irregular shedding produced by the grill gives rise to a more random type of boundary layer turbulence than does the tripping

* At a given Reynolds number, frequencies which yield disturbances to the right of the upper branch of the stability curve are considered high frequencies.

wire. As has been discussed earlier, no such forestalling of turbulence, as observed for the tripping wire, is noted in the case of the grill.

Localized nonlinear acoustic phenomena, as discussed earlier, appear to have no effect on the incipient boundary layer disturbances, since most of the observed effects can be correlated reasonably well with what one might expect on the basis of conventional stability theory. It is also found that localized sonic excitation has no observable effect on the mean velocity profile in the laminar flow regime.

It thus appears that localized sonic excitation of a boundary layer cannot forestall normal transition from laminar to turbulent flow. However, what the extent of its beneficial effects may be in terms of affecting heat transfer and drag characteristics of aero-dynamic bodies remains an open question.

Studies by other investigators (Refs. 18, 19) have indicated that sonic excitation can greatly increase rate of heat transfer from a body, and also can be used to achieve reductions in overall drag. In the former situation, one would expect that premature initiation of turbulence would indeed lead to increased rates of heat transfer from an object exposed to flow. However, the mechanisms involved in achieving drag reduction by acoustic means remains unknown.

SECTION VIII

AREAS FOR FURTHER STUDY

Results of our present investigations indicate that a promising approach to developing more understanding of the influence of surface initiated sonic excitation on boundary layer stability can be obtained by employing a distributed source of sound in place of the localized sonic excitation system presently in use. In this way it should be possible to generate disturbances that have the behavior of surface waves; i.e., they are in essence, restricted to a thin layer in the vicinity of the surface of the test body. As a matter of fact, the localized source used at present has the disadvantage that its acoustic field is spherically symmetric; its influence is felt equally in perpendicular and parallel directions to the wall. On the other hand, a distributed source can be arranged so that contiguous source elements are out of phase, thus cancelling out most of the local symmetric pressure field, and leaving a local velocity field primarily oriented parallel to the wall, i.e., in the boundary layer.

In a normal boundary layer flow, transition will occur at some point on the test body even in the absence of sonic excitation. In principle, it seems feasible that such transition could be influenced by producing a wave at the surface of the test body in such a way as to cancel the incipient Tollmien-Schlichting wave in the boundary layer, thereby forestalling transition. Production of such a wave could be accomplished by use of a distributed source. We have not investigated the practicability of such a system for controlling boundary layer transition. We do, however, believe that such an experiment would be worthwhile for it should lead to a greater understanding of the transition process itself.

It is worth noting that recent experimental work performed by Kramer (Ref. 20) has shown that considerable reductions in the hydrodynamic drag of an underwater solid body can be achieved by covering it with a skin of flexible material. This effect has been ascribed to the fact that the boundary layer remains laminar in the presence of the skin; i.e., transition is delayed.

It has been postulated that the mechanism whereby such a delay in transition is achieved arises from a damping of incipient Tollmien-Schlichting waves by the viscoelastic material which composes the flexible skin. Thus, boundary layer oscillations which would tend to amplify as they propagate downstream are assumed to be damped out, with the result that the flow remains laminar.

Recently, Brooke-Benjamin (Ref. 21) has presented a theory of linear stability of flow over a compliant surface, i.e., one which can support wave motion at the fluid-solid interface. Briefly, he concludes

that, depending upon the damping characteristics and the compliance of the material, as well as the relationship of the free wave speed in the material to the speed of incipient Tollmien-Schlichting waves, the flexible boundary can have either a stabilizing or destabilizing influence on the flow. One unexpected result of this theory is that in certain cases it appears that the flow can actually be stabilized by decreasing the amount of damping associated with the flexible coating, which in a sense amounts to redistributing energy in the thin layer of fluid contiguous to the wall in such a way as to reduce the influence of viscosity as a cause of transition in the boundary layer. On the basis of Brooke-Benjamin's studies it appears that the stabilization effects referred to above cannot be explained simply on the basis of a damping mechanism, and hence there is still some question as to what is the precise mechanism whereby transition is delayed. One may, however, infer that the transition delay is in some way connected with the propagation of "surface" type waves in the compliant medium which are excited by the boundary layer oscillations in the fluid. It would thus appear promising to study the active analog of the systems described above, namely, one in which a surface wave is generated at a surface exposed to a shear flow.

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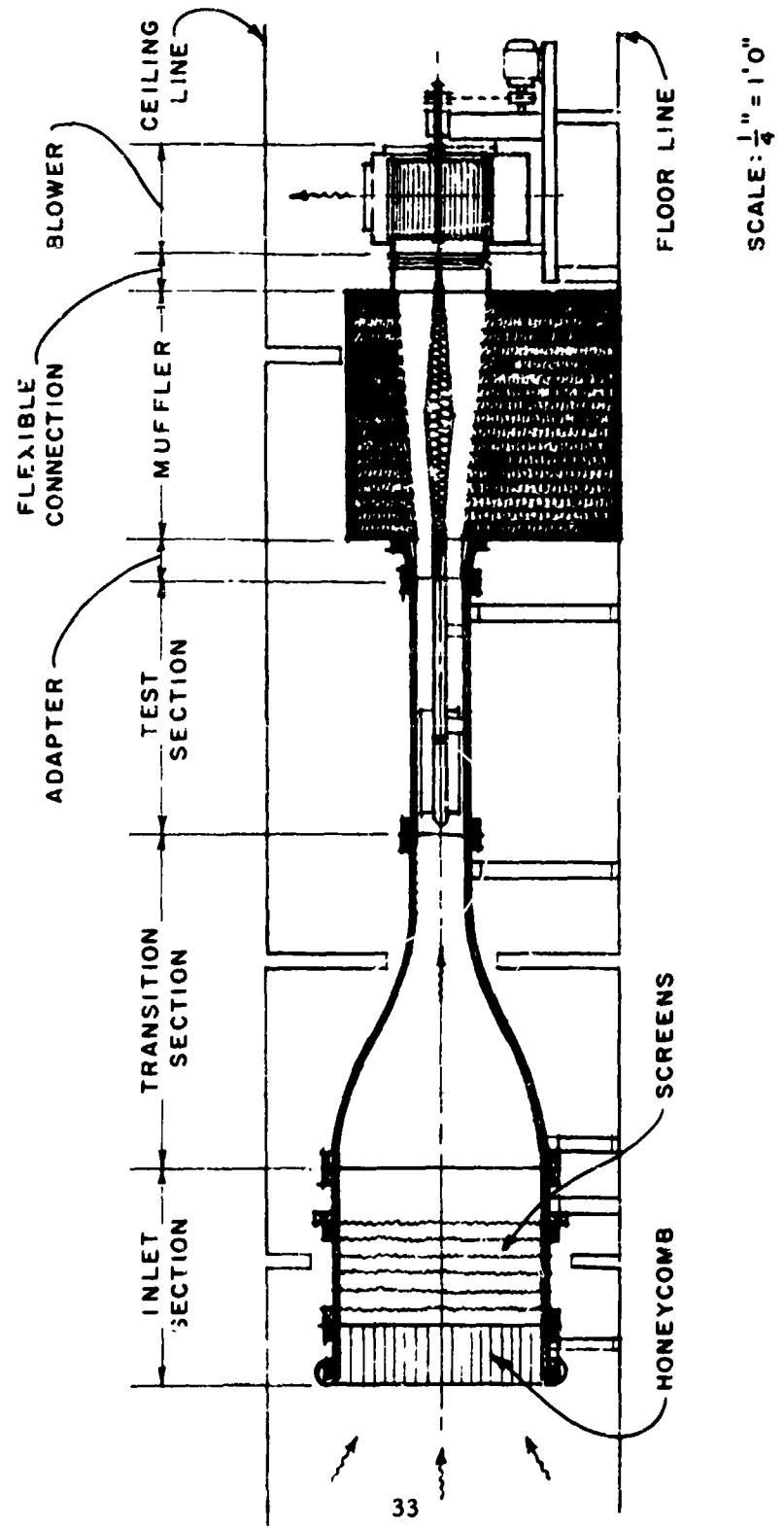


FIG. 1 CROSS SECTIONAL VIEW OF THE WIND TUNNEL

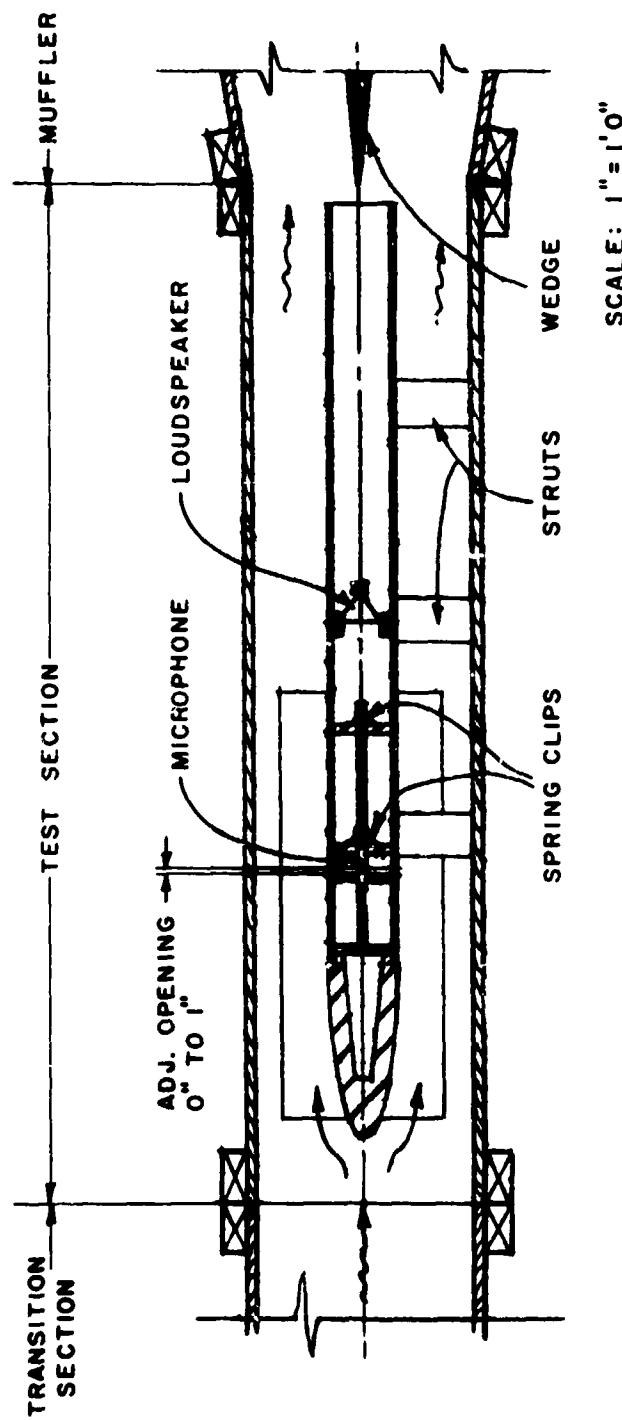


FIG. 2 CROSS SECTIONAL VIEW OF THE TEST BODY AND SONIC EXCITATION SYSTEM

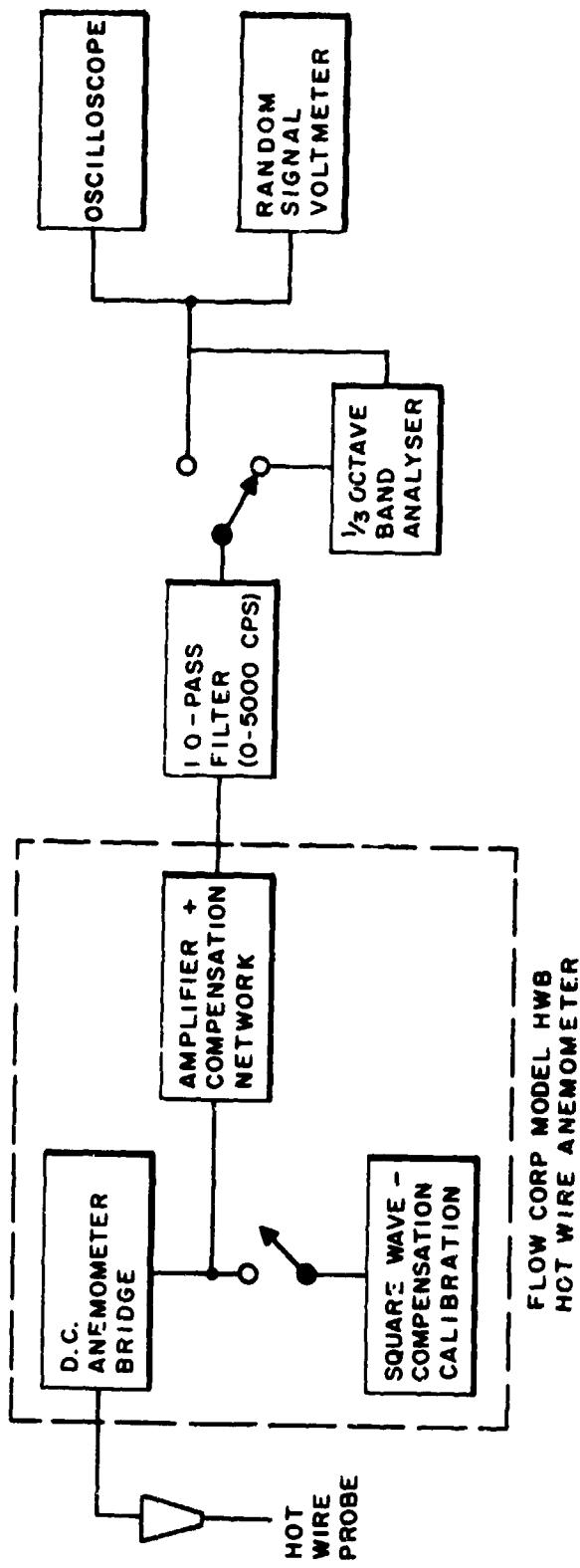


FIG. 3 BLOCK DIAGRAM OF HOT WIRE ANEMOMETER SYSTEM

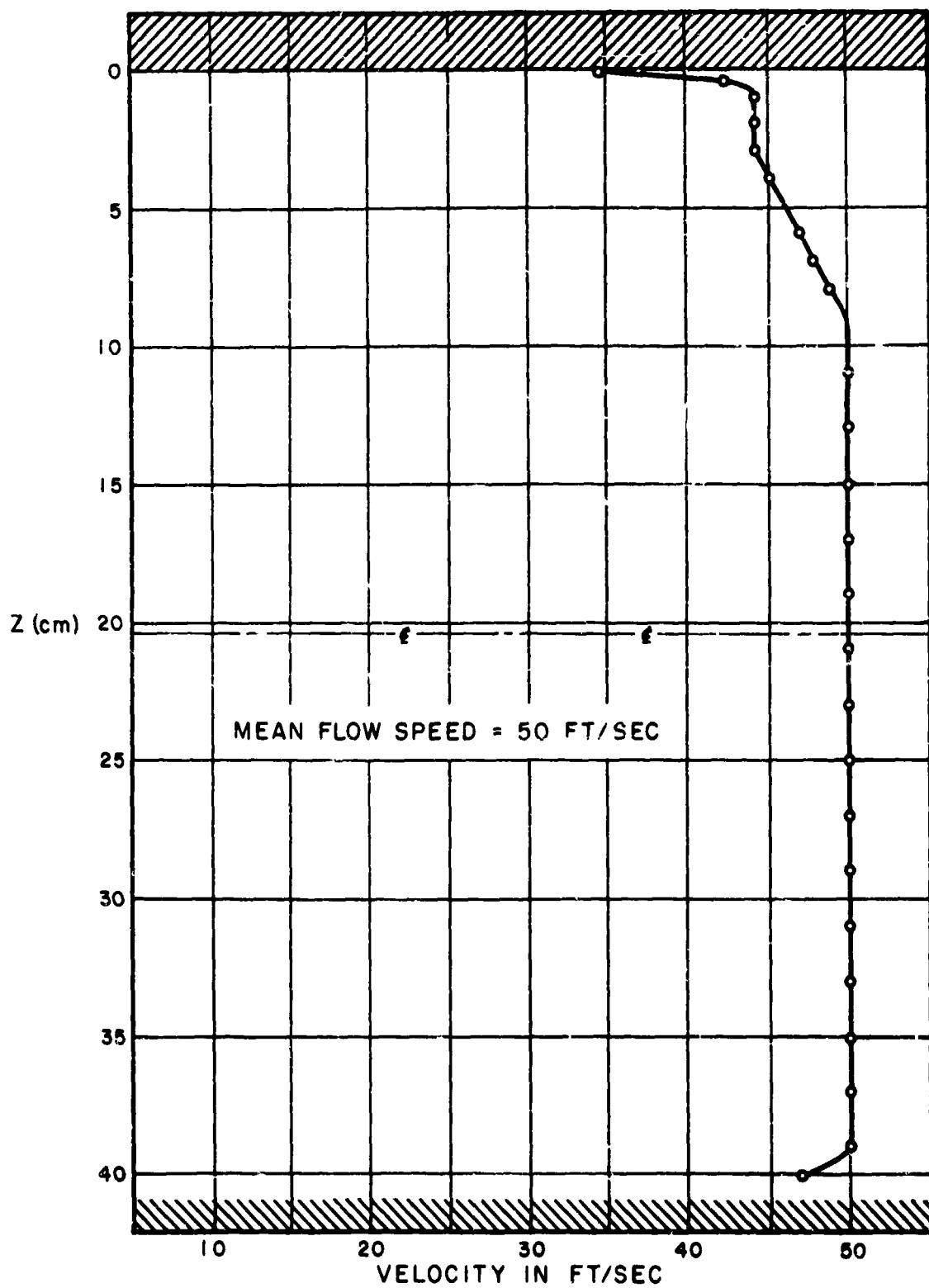


FIG. 4 D.C. VELOCITY DISTRIBUTION ACROSS TEST SECTION

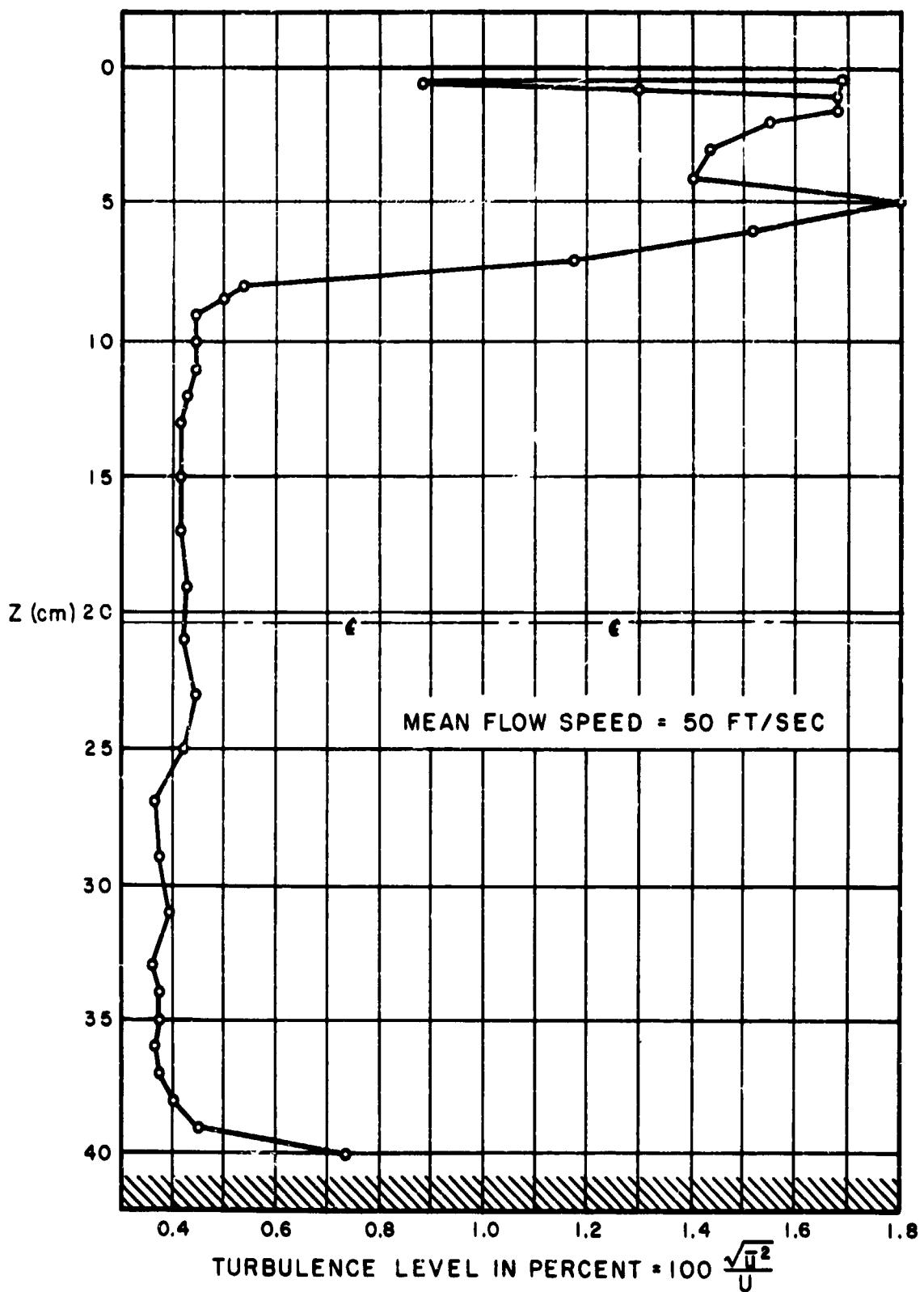


FIG. 5 TURBULENCE LEVEL VERTICAL DISTRIBUTION IN TEST SECTION - TEST BODY ABSENT

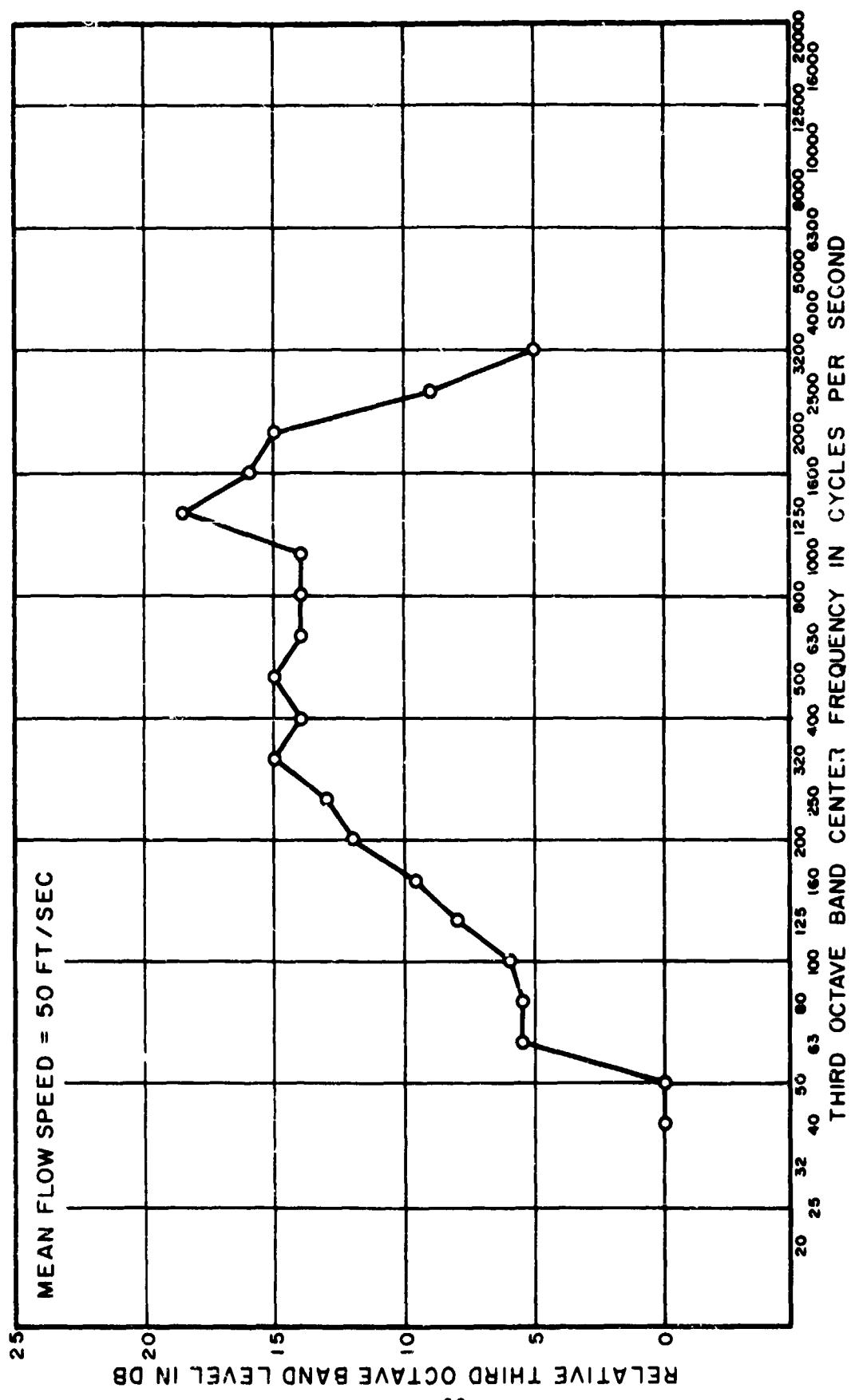


FIG. 6 TYPICAL TURBULENCE SPECTRUM NEAR CENTER OF TEST SECTION

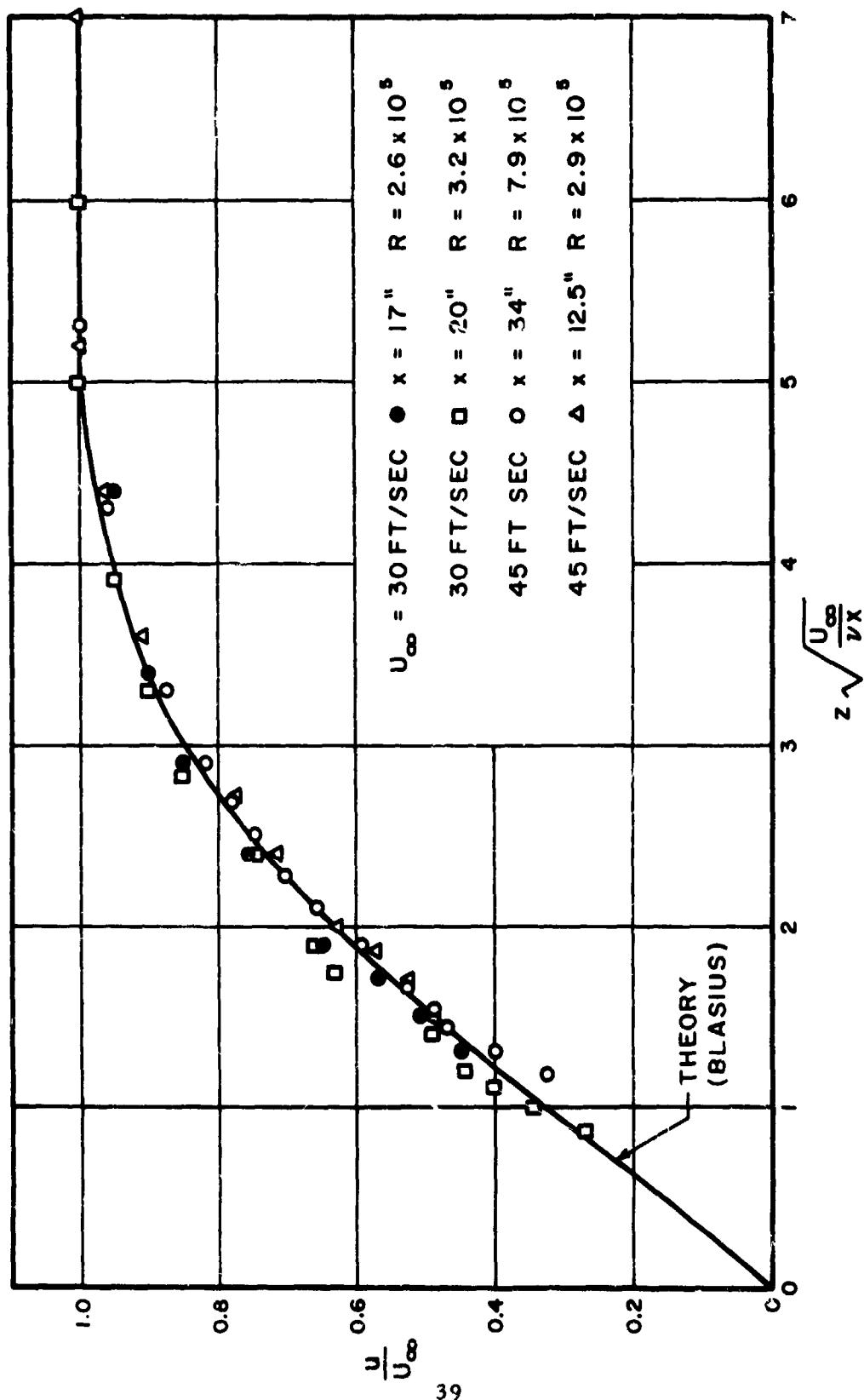


FIG. 7 MEASURED D.C. VELOCITY DISTRIBUTION ACROSS THE LAMINAR BOUNDARY LAYER ON THE TEST BODY

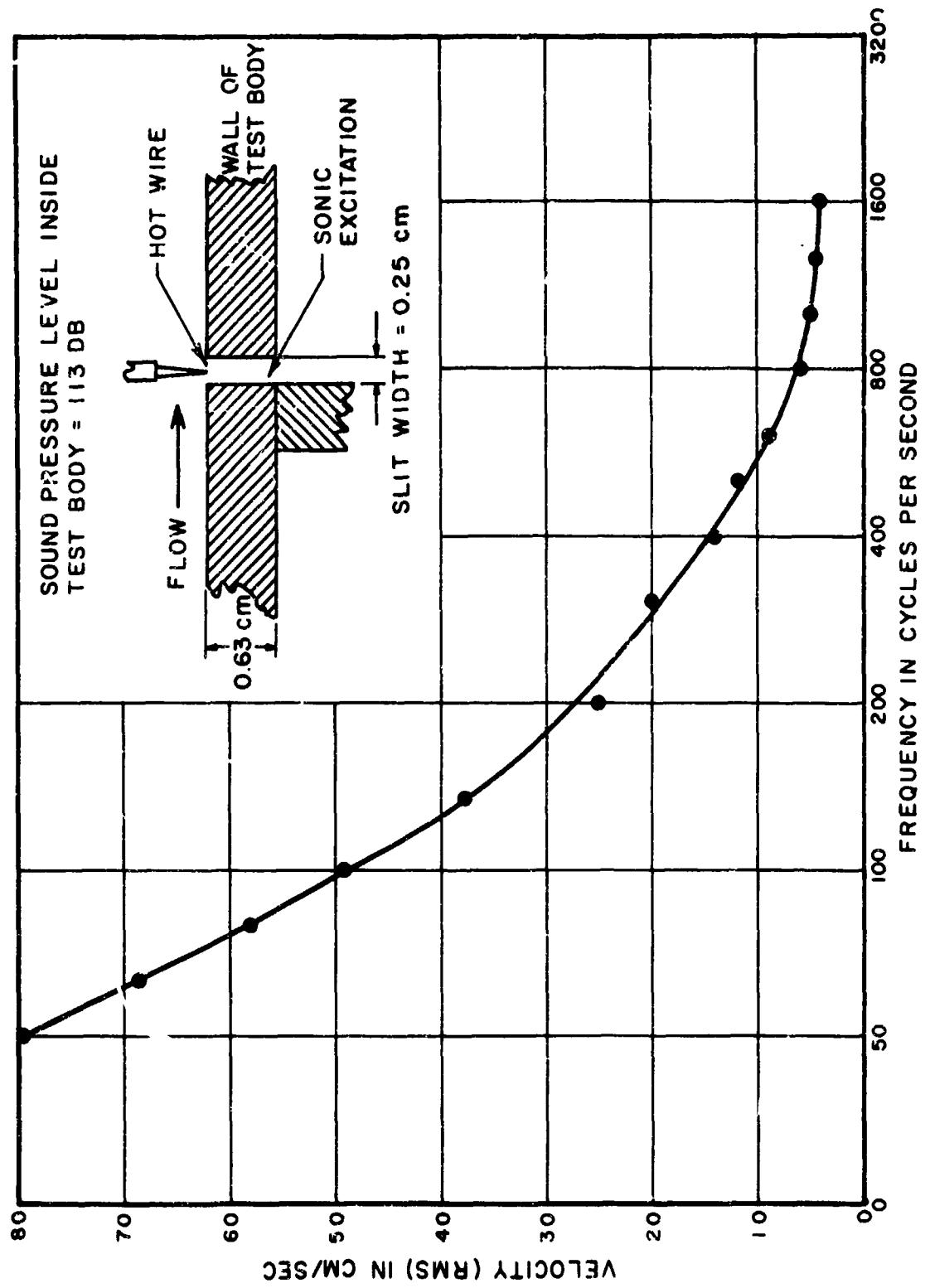


FIG. 8 OSCILLATORY VELOCITY AT THE CIRCUMFERENTIAL SLIT VS. FREQUENCY - CONSTANT EXCITATION LEVEL

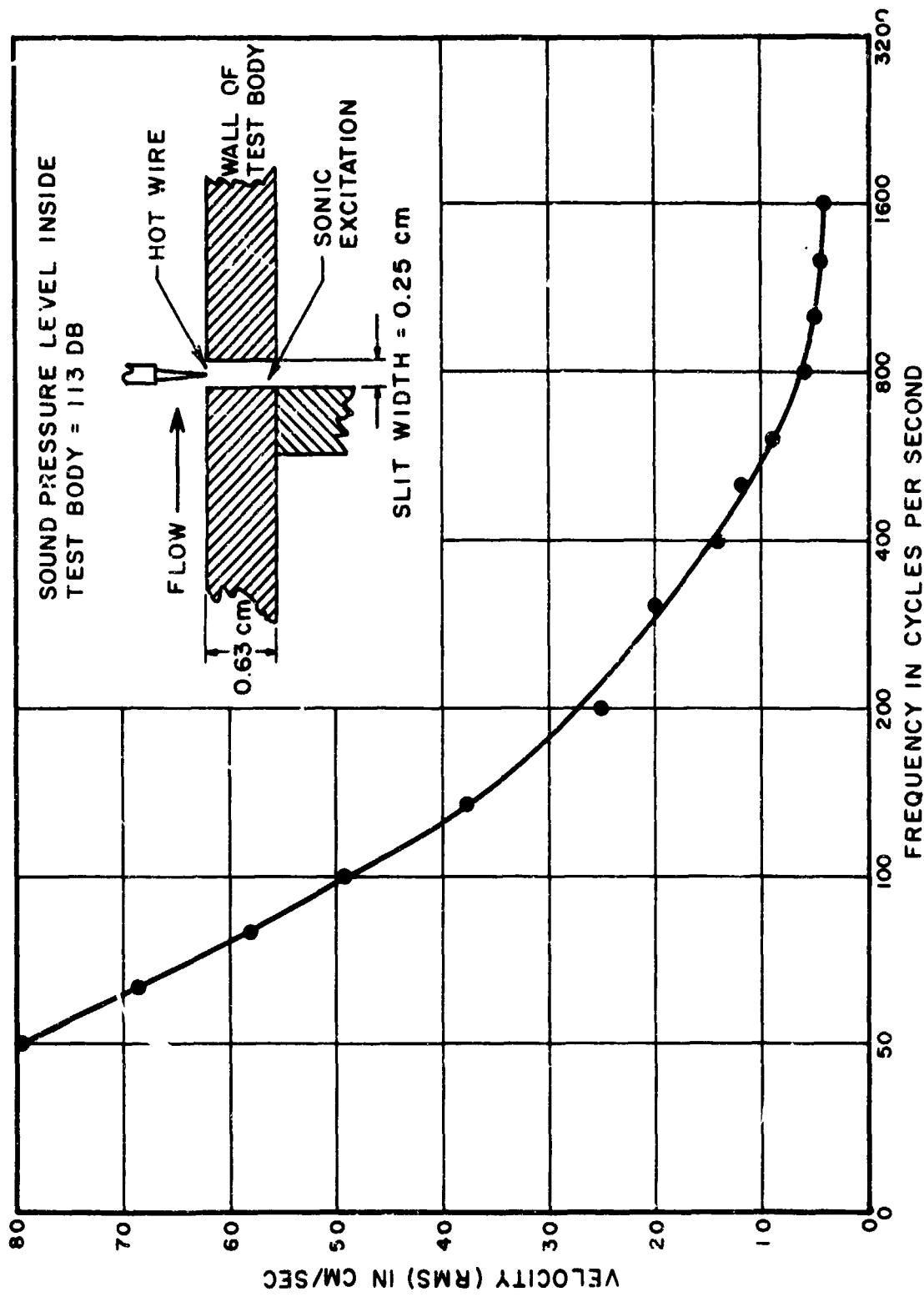


FIG. 8 OSCILLATORY VELOCITY AT THE CIRCUMFERENTIAL SLIT VS. FREQUENCY - CONSTANT EXCITATION LEVEL

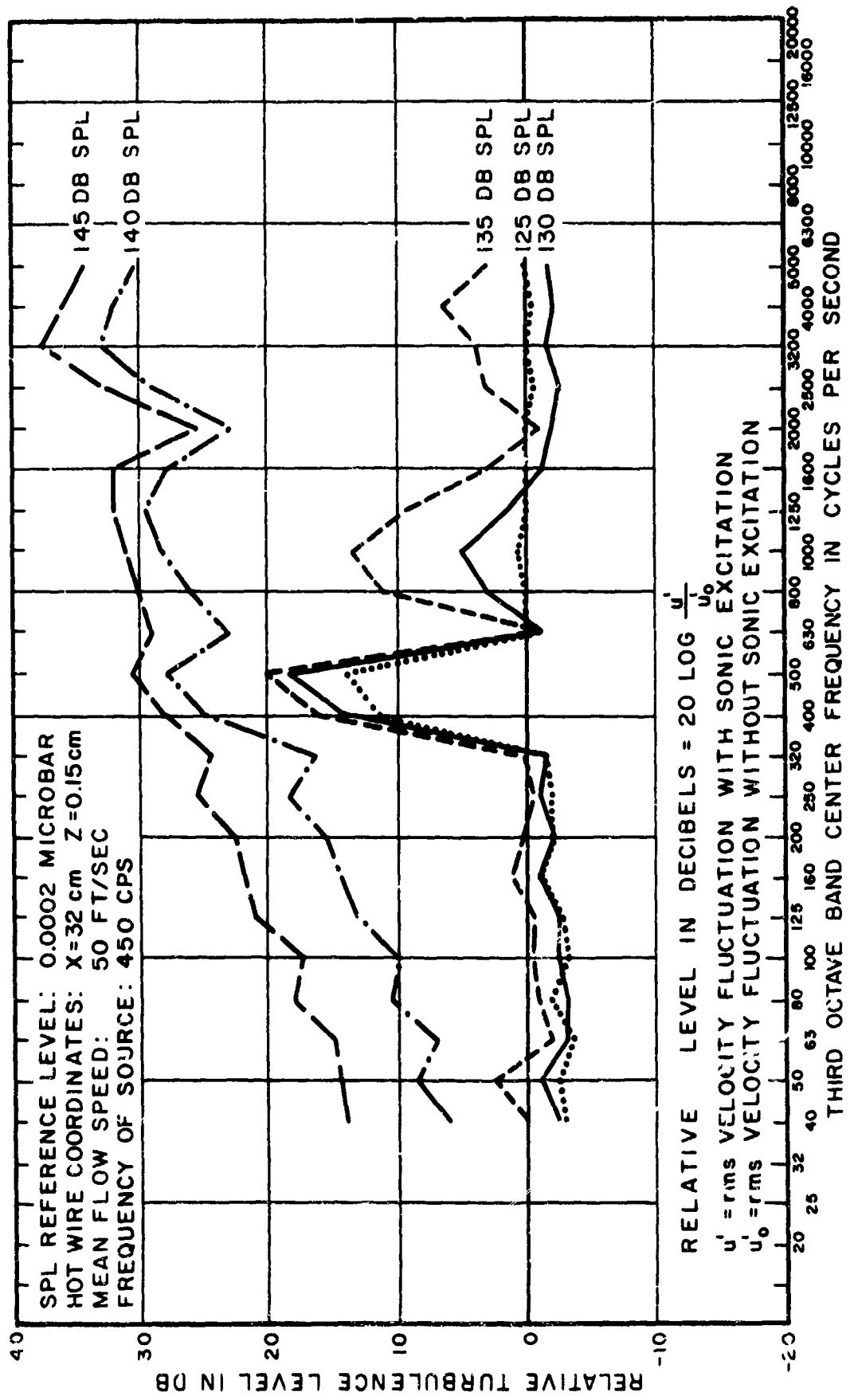


FIG. 10 TURBULENCE SPECTRA FOR VARIOUS SONIC EXCITATION LEVELS

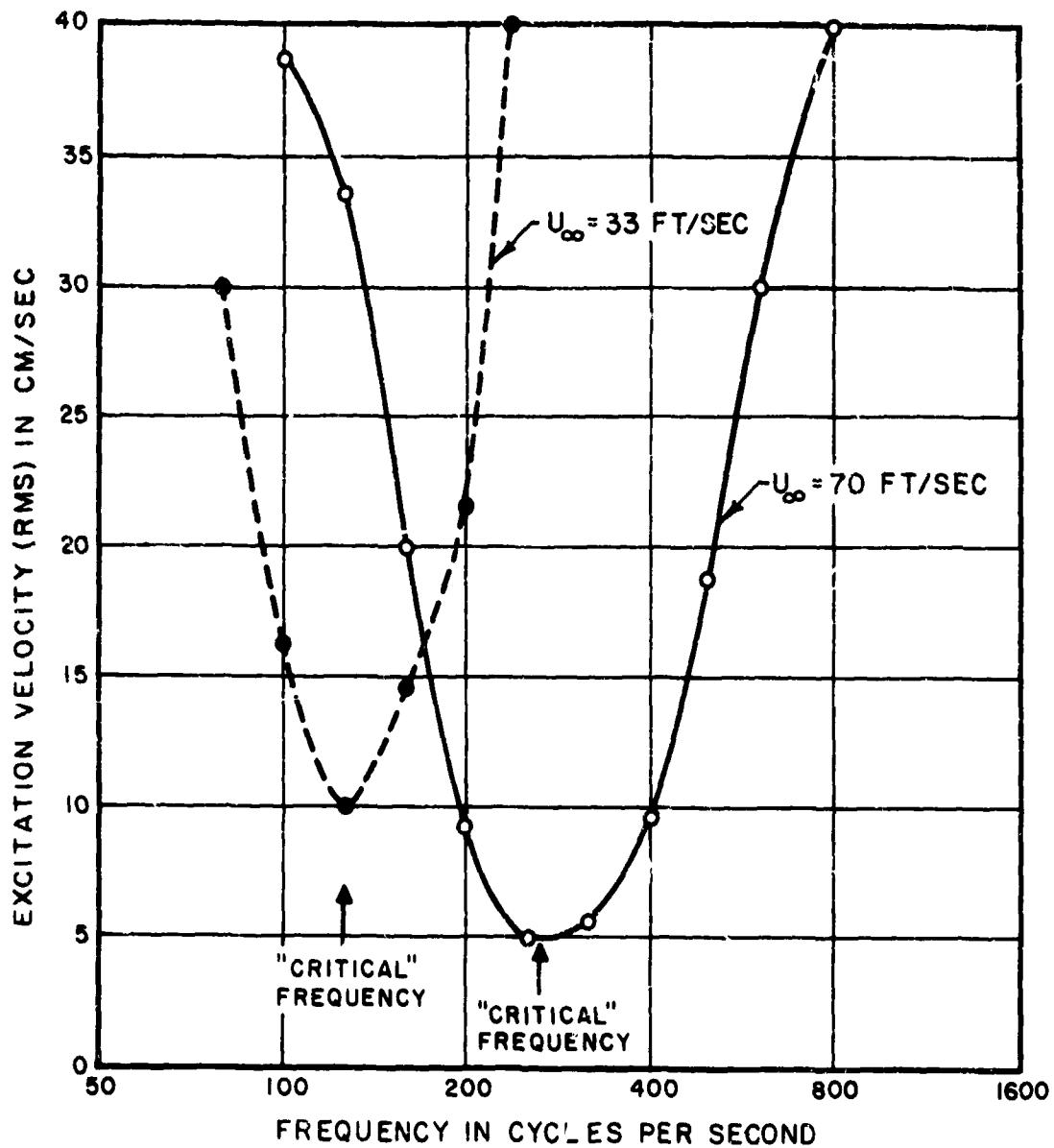


FIG. II EXCITATION OF TURBULENCE BY SOUND
 (THE CURVES GIVE THE PARTICLE VELOCITY AT
 THE SLOT THAT WAS NECESSARY TO CAUSE
 TURBULENCE AT $x = 27"$

(6) : 345

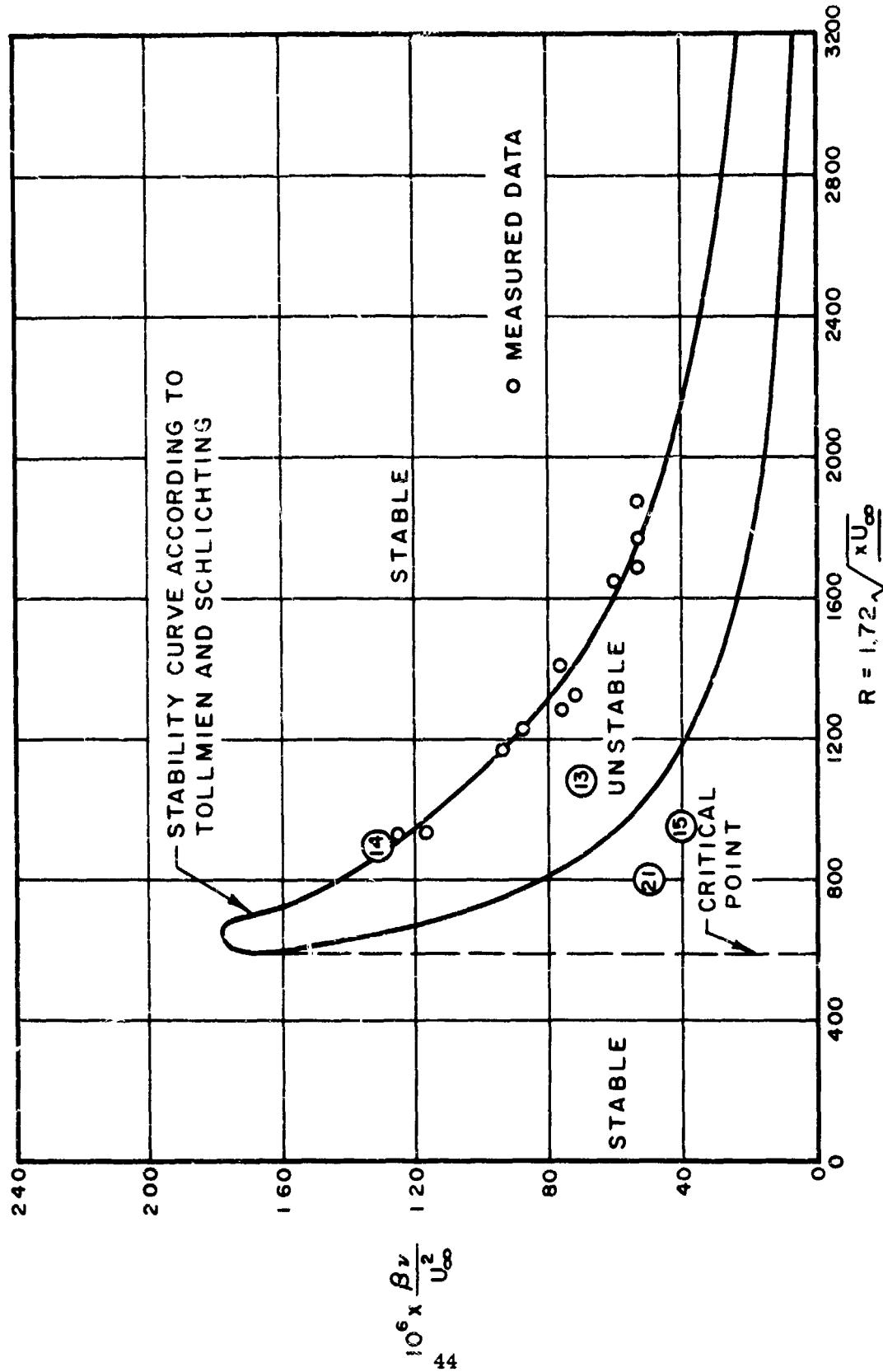


FIG. 12 COMPARISON OF THE "CRITICAL" FREQUENCIES WITH THE THEORETICAL STABILITY CURVE

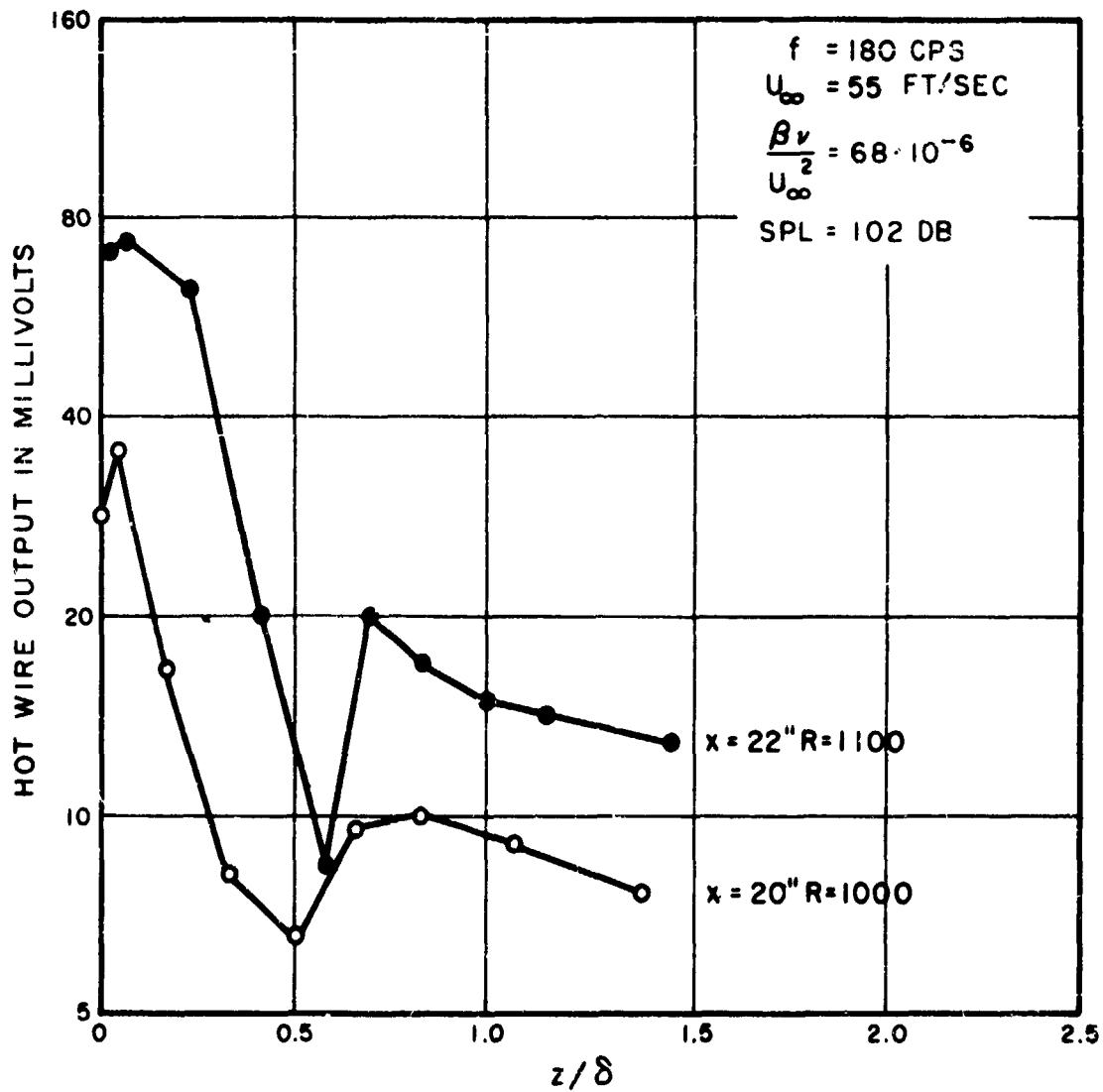


FIG. 13 A.C. VELOCITY PROFILE AS FUNCTION OF DISTANCE FROM TEST BODY

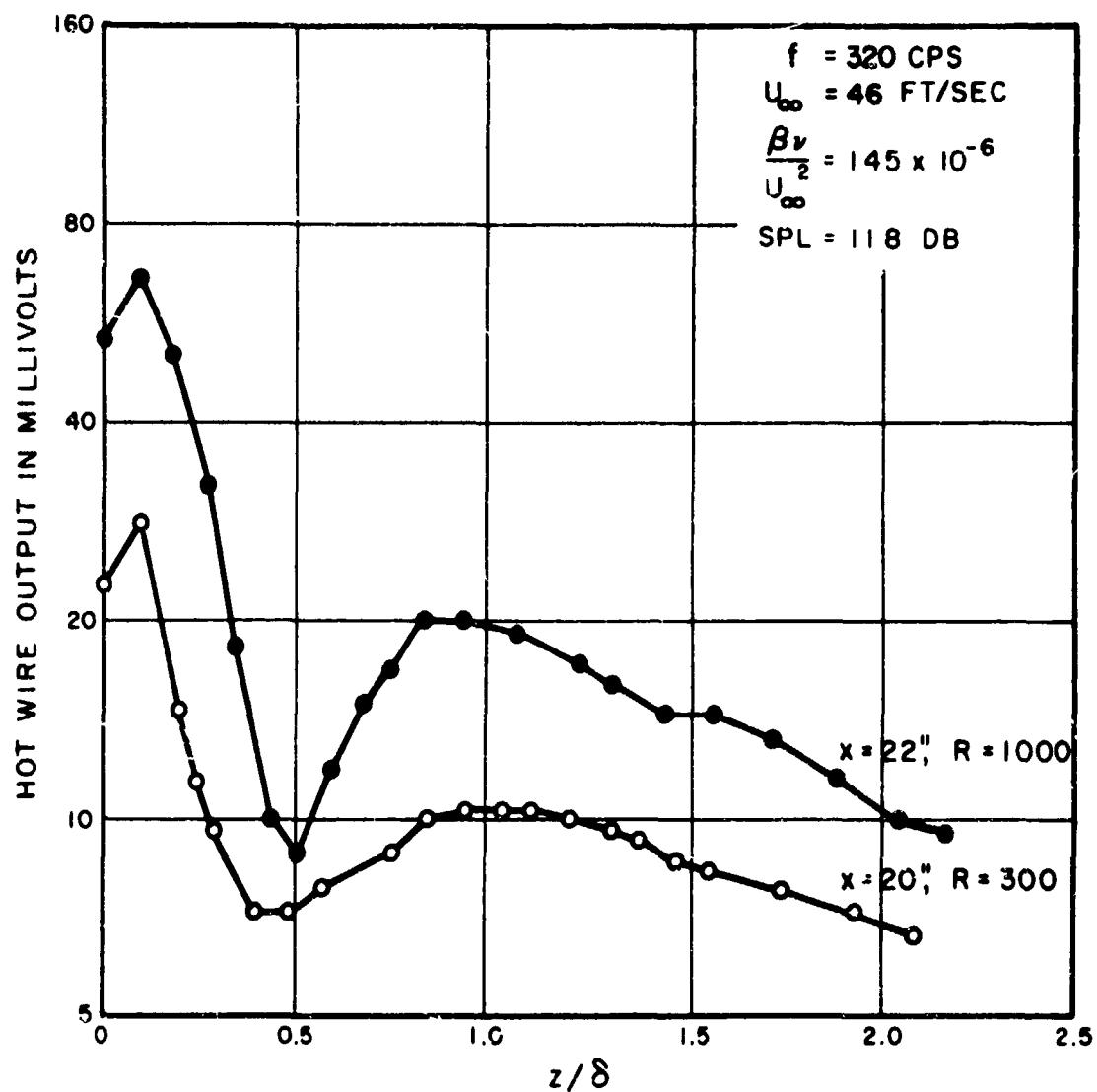


FIG. 14 A.C. VELOCITY PROFILE AS FUNCTION OF DISTANCE FROM TEST BODY

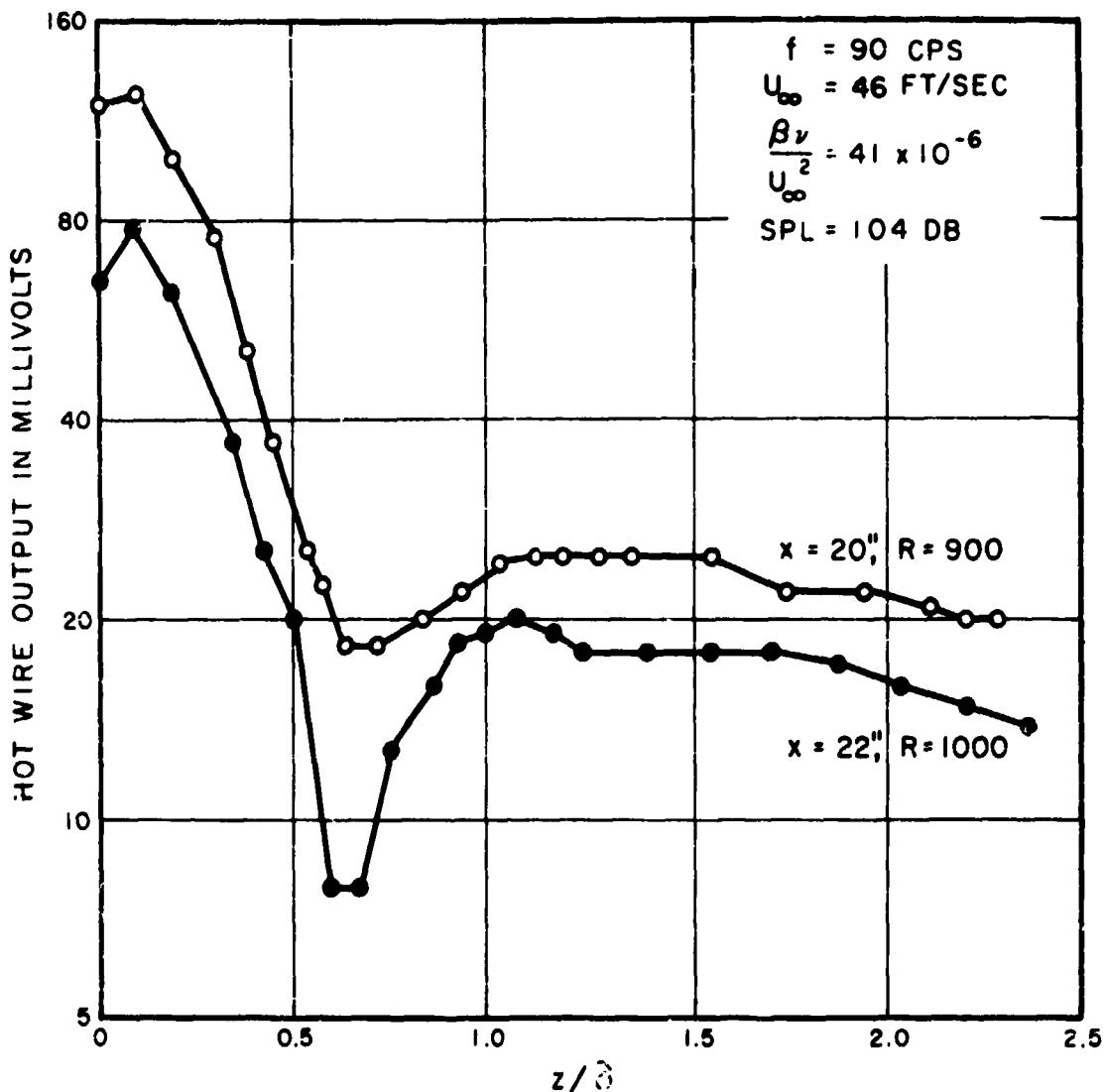


FIG.15 A.C. VELOCITY PROFILE AS FUNCTION OF DISTANCE FROM TEST BODY

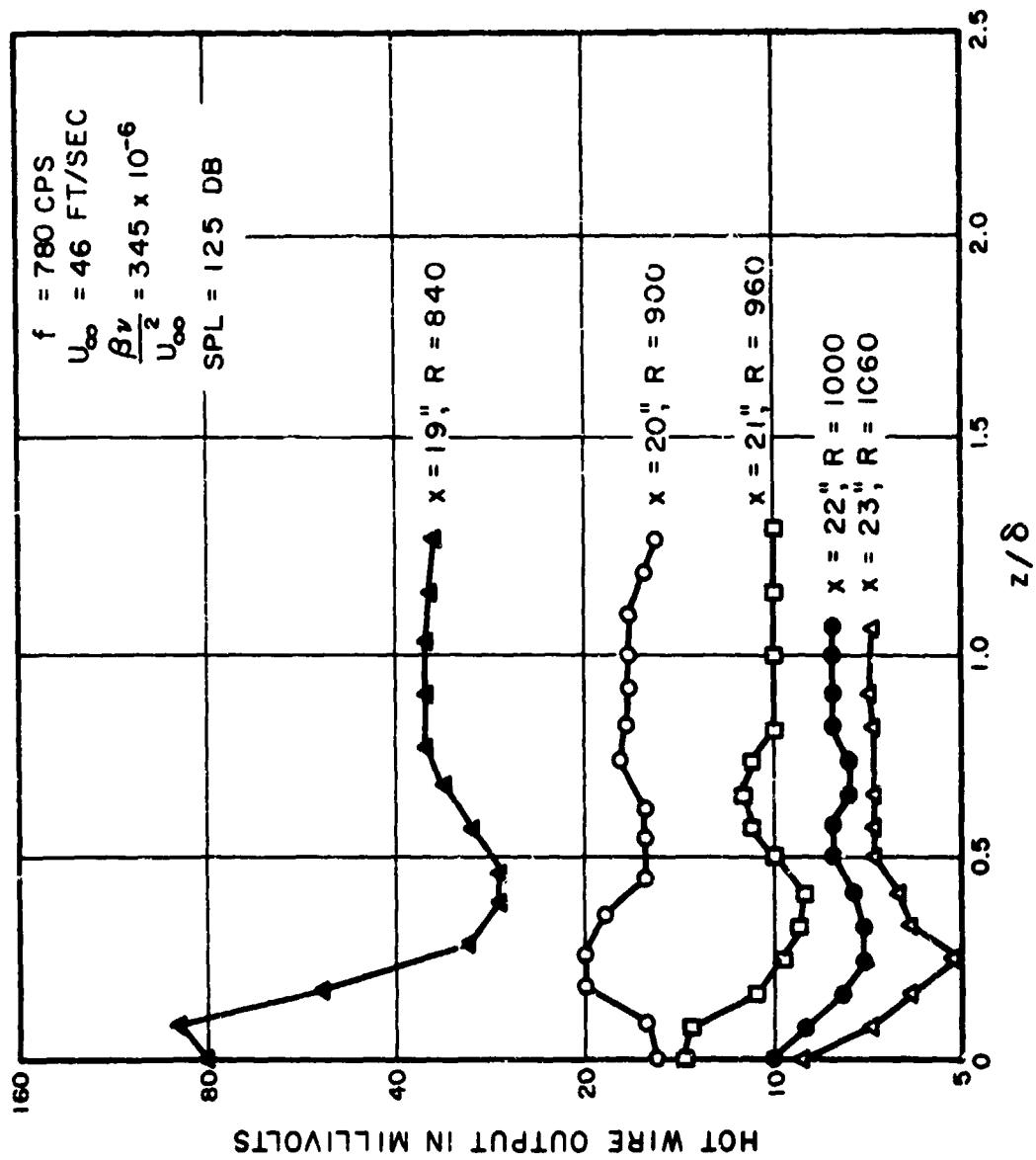


FIG.16 A.C. VELOCITY PROFILE AS FUNCTION OF DISTANCE FROM TEST BODY

SPL
100 DB



103 DB

SPL
102 DB

2.5 106 DB

108 DB

5 129 DB



5

5

117 CPS, $x = 14"$

157 CPS, $x = 14"$

MEAN FLOW SPEED = 46 FT / SEC.

SPL
133 DB

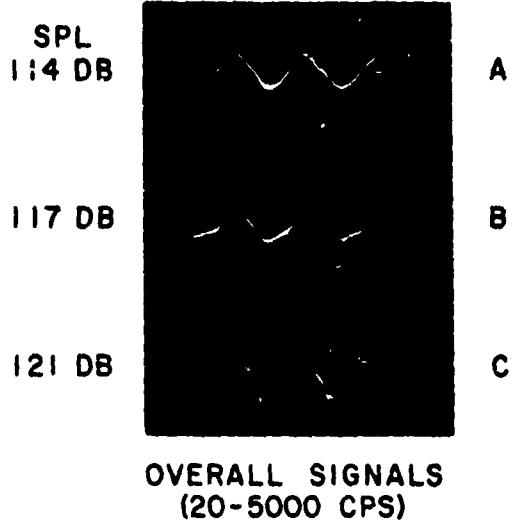


134 DB

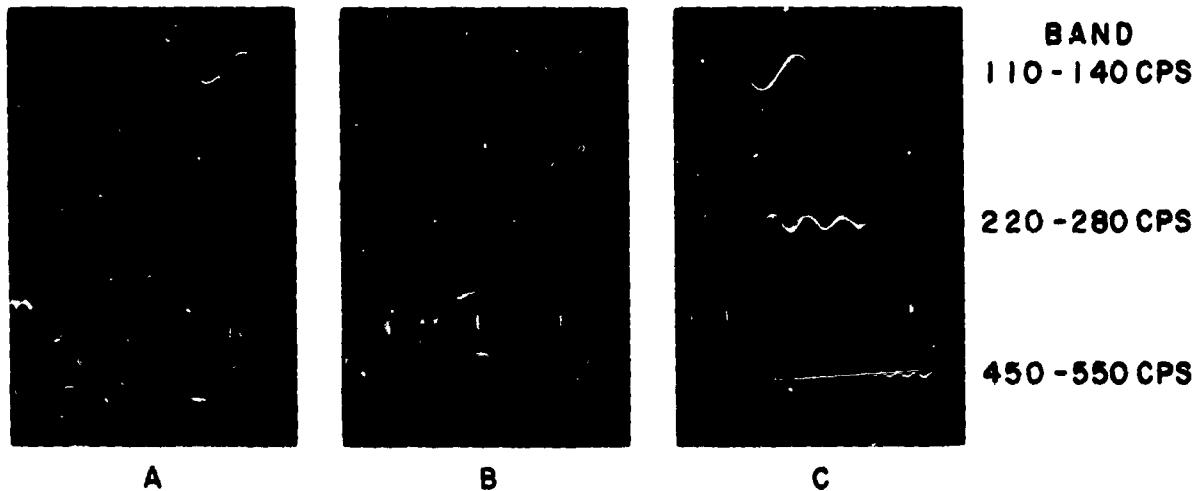
136 DB

450 CPS, $x = 8.5"$

FIG. 17 BOUNDARY LAYER DISTURBANCES FOR VARIOUS EXCITATION FREQUENCIES AND AMPLITUDES



ONE-THIRD OCTAVE BAND ANALYSIS OF ABOVE SIGNALS



$x = 21''$
MEAN FLOW SPEED = 45.2 FT/SEC
EXCITATION FREQUENCY = 125 CPS

FIG. 18 BOUNDARY LAYER DISTURBANCES FOR VARIOUS EXCITATION AMPLITUDES - HARMONIC ANALYSIS



100 CPS

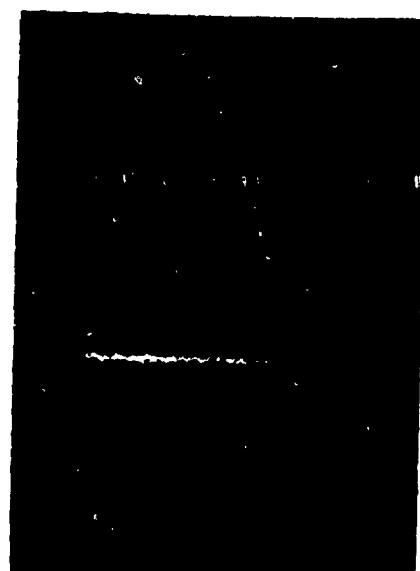


200 CPS

MEAN FLOW SPEED = 46 FT./SEC.



450 CPS



780 CPS

FIG. 19 BOUNDARY LAYER FLUCTUATIONS AT VARIOUS DISTANCES
DOWNSTREAM OF THE LOCALIZED SOUND SOURCE LOCATED
AT $X = 12"$

$x = 22"$



A

$x = 23"$

B

$x = 24"$

C

OVERALL SIGNALS
(20 - 5000 CPS)

ONE-THIRD OCTAVE BAND ANALYSIS OF ABOVE SIGNALS



BAND
110 - 140 CPS

220 - 280 CPS

450 - 550 CPS



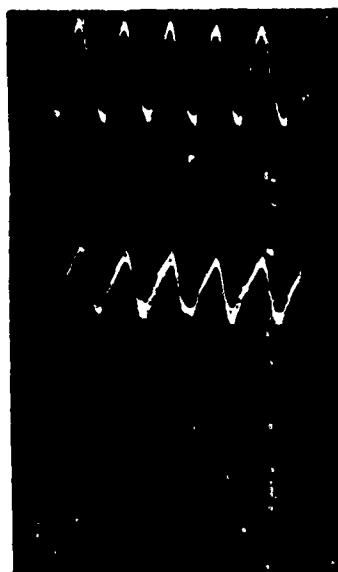
C

SPL = 112 DB

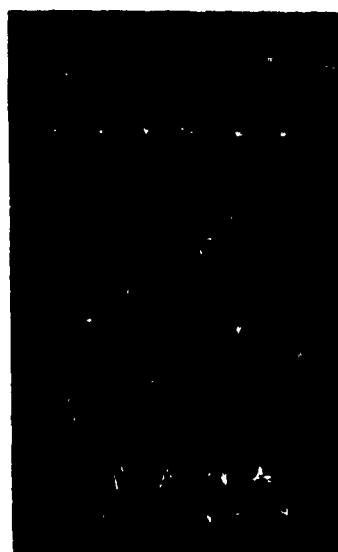
MEAN FLOW SPEED = 45.2 FT/SEC

EXCITATION FREQUENCY = 125 CPS

FIG. 20 BOUNDARY LAYER DISTURBANCES AT VARIOUS
DOWNSTREAM POINTS - HARMONIC ANALYSIS



OVERALL

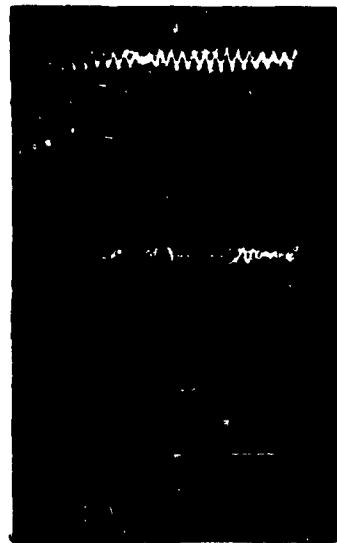


90 - 110 CPS



180 - 220 CPS

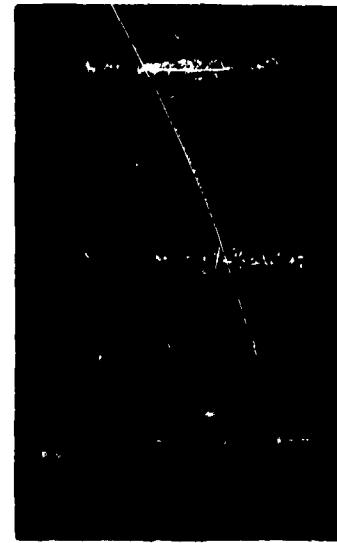
MEAN FLOW SPEED - 46 FT./SEC.



360 - 440 CPS



720 - 880 CPS



1500 - 1700 CPS

$x = 6"$

$x = 7.3"$

$x = 10"$

$x = 6"$

$x = 7.3"$

$x = 10"$

FIG. 21 SPECTRUM ANALYSIS OF SONICALLY INDUCED BOUNDARY LAYER FLUCTUATIONS AT VARIOUS DISTANCES ALONG TEST BODY

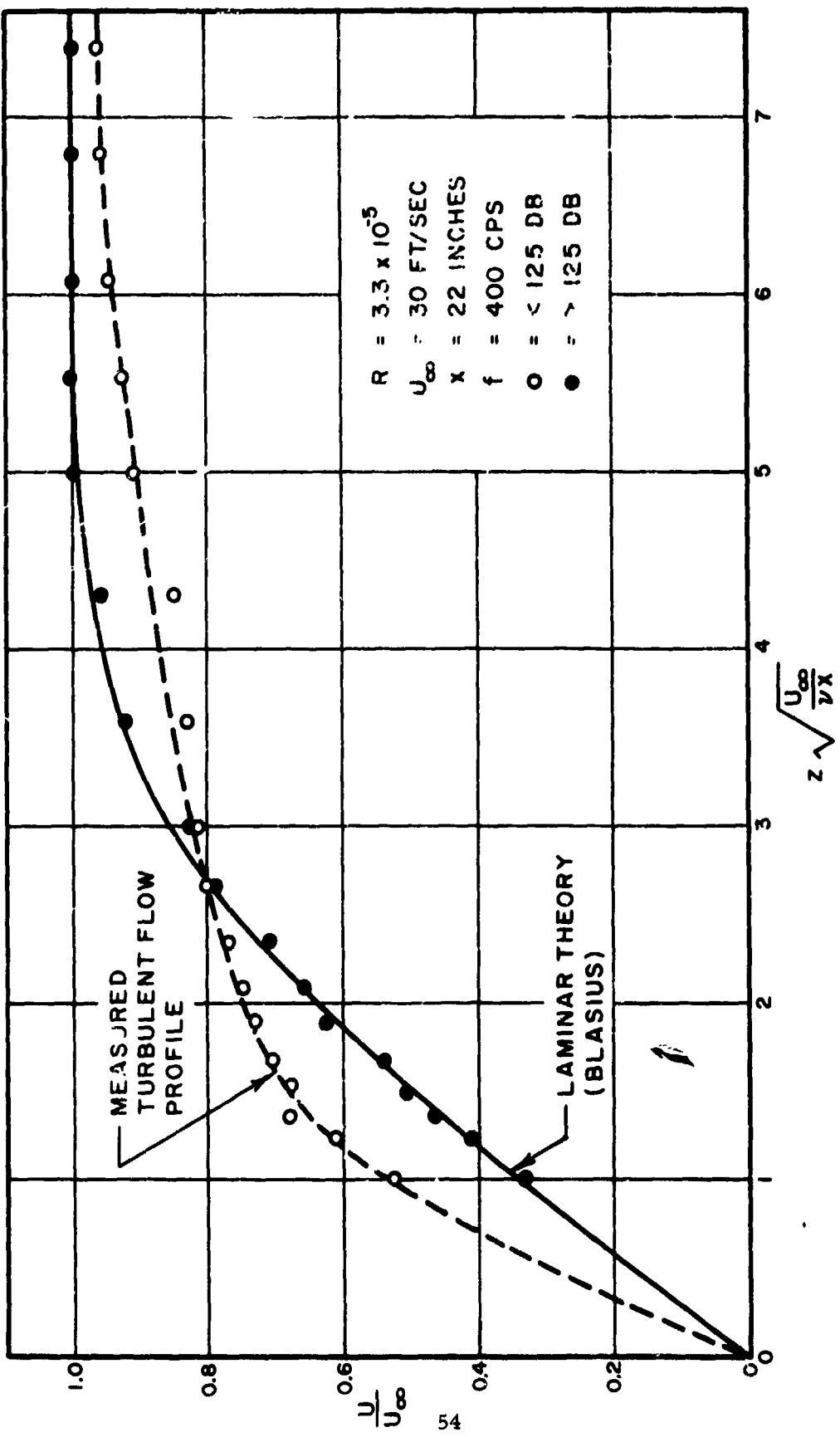


FIG. 22 MEAN VELOCITY PROFILES OBTAINED IN THE PRESENCE OF SONIC EXCITATION

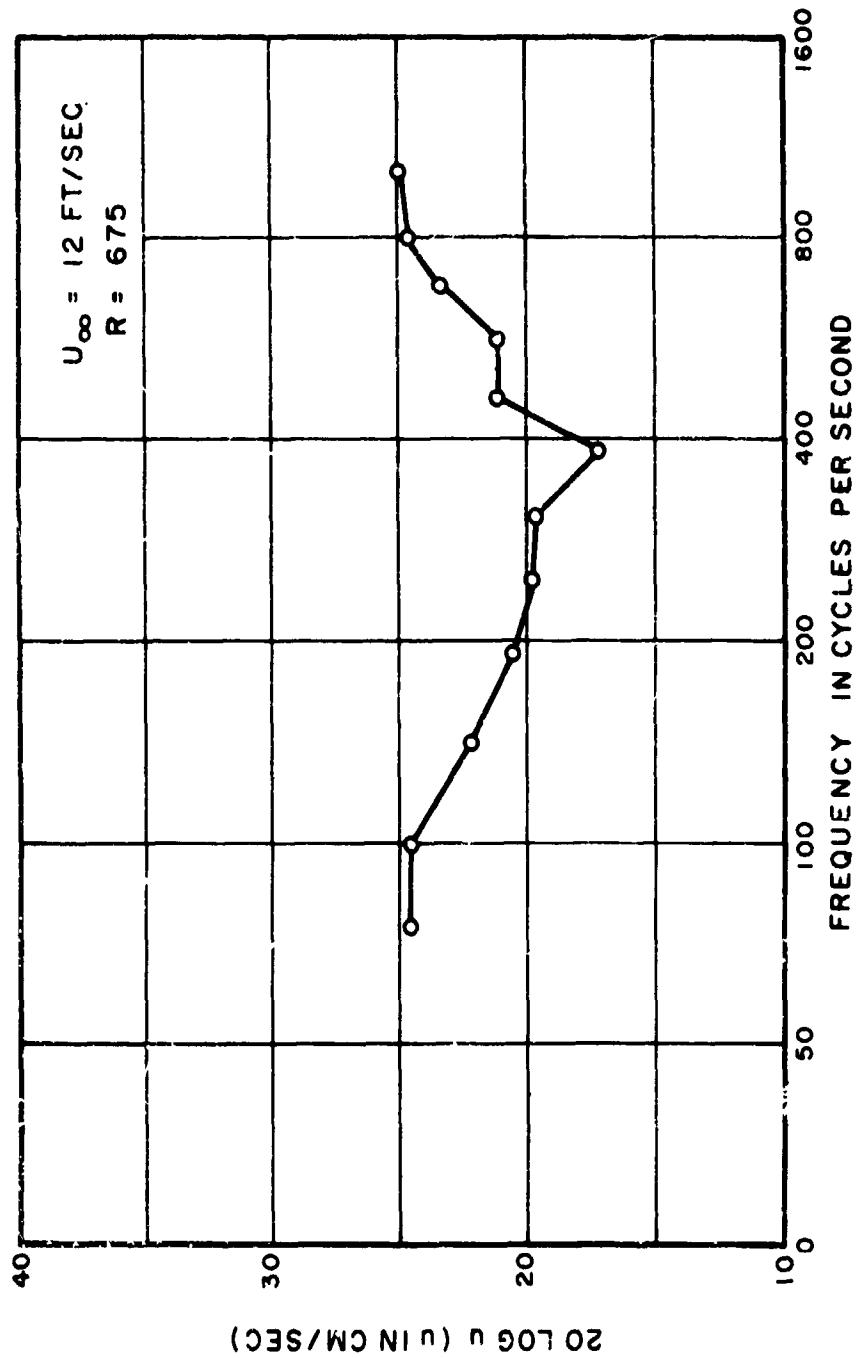


FIG. 23 MINIMUM SOUND PARTICLE VELOCITIES REQUIRED
 TO CAUSE TRANSITION FOR A FREE STREAM
 TURBULENCE LEVEL OF 1.3 PERCENT

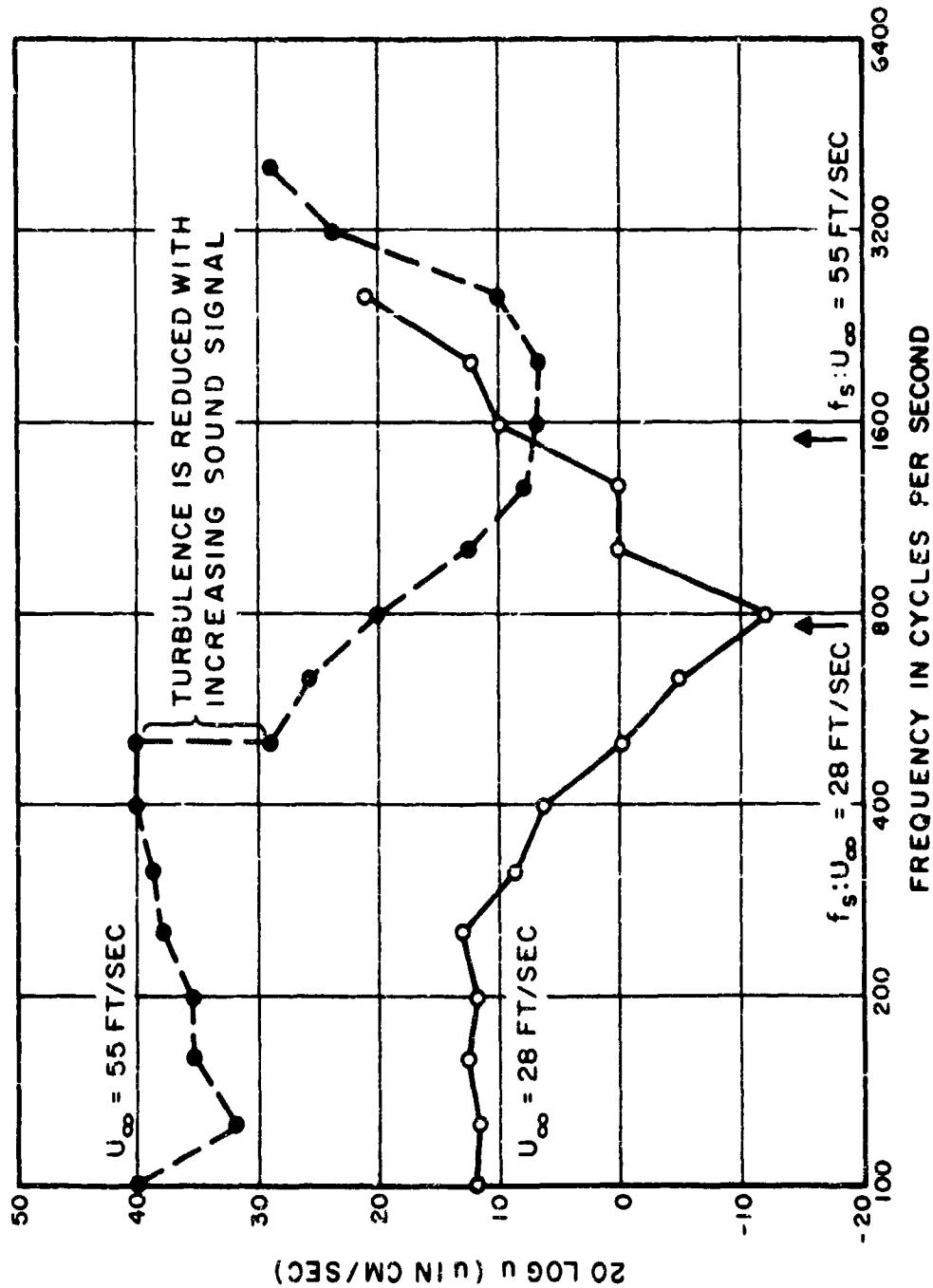


FIG.2.4 MINIMUM SOUND PARTICLE VELOCITIES REQUIRED TO CAUSE TURBULENCE IN THE PRESENCE OF A TRIPPING WIRE

UNCLASSIFIED

Acronautical Research Laboratories, Wright-Patterson AFB, Ohio. EFFECT OF LOCALIZED ACOUSTIC EXCITATION ON THE STABILITY OF A LAMINAR BOUNDARY LAYER LAYER by Francis J. Jackson, Manfred A. Heckl, Bolt Beranek and Newman, Inc. Cambridge, Mass. June 1962. 56 p. illus. (Project 7064, Task 70138) (Contract AF 33 (616)-8001) (ARL 62-362)

Unclassified Report

As a part of a program to uncover the influence of induced surface vibrations on the stability of a shear flow boundary layer, investigations have been performed utilizing

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a localized surface source of acoustic energy to generate disturbances in a laminar boundary layer flow

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